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GASS High Velocity Clouds in the Region of the Magellanic Leading Arm

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ABSTRACT

We present a new catalog of high-velocity clouds in the region of the Magellanic Leading Arm. The catalog is based on neutral hydrogen (HI) from the Parkes Galactic All-Sky Survey (GASS). Excellent spectral resolution allows clouds with narrow-line components to be resolved. The total number of detected clouds is 407. We describe the method of cataloging and present the basic parameters of the clouds. We discuss the general distribution of the high-velocity clouds and classify the clouds based on their morphological type. The presence of a significant number of head-tail clouds and their distribution in the region is compared with simulations. We suggest that ram-pressure stripping is a more important factor than tidal forces for the morphology and formation of the Magellanic Leading Arm and that different environmental conditions might explain the morphological difference between the Magellanic Leading Arm and Magellanic Stream. Using the velocity structure of the Leading Arm we derive the distance for the clouds to be ~ 30 kpc. We also report a new population of clouds that forms the LA IV and a new diffuse bridge-like feature connecting the Leading Arm II and III complexes.

Subject headings: Galaxy: halo – intergalactic medium – ISM: HI– Magellanic Clouds

1. INTRODUCTION

Some atomic neutral hydrogen (HI) concentrations surrounding our Galaxy have anomalous velocities that are forbidden by a simple Galactic rotation model. These so-called

anomalous-velocity clouds contain H I without a stellar counterpart. They can be classified into two velocity based groups: intermediate velocity clouds (IVCs; Münch & Zirin 1961; Blaauw & Tolbert 1966); high-velocity clouds (HVCs; Muller et al. 1963). The classification of IVCs and HVCs is based on the deviation velocity, which is defined as the smallest difference between the velocity of the cloud and the Galactic rotational velocity (Wakker 1991). High-velocity clouds are particularly interesting because they are thought to represent the flow of baryons in or out of the Galactic disk, which influences the formation and evolution of our Galaxy. Despite being important in the context of galaxy formation and evolution, their origin and physical characteristics are still under debate.

Possible explanations of the origin of HVCs can be traced back to an early study by Oort (1966). One of his hypotheses suggested that the HVCs have an extragalactic origin. This hypothesis received more recent support from Blitz et al. (1999) with the argument that HVCs are dark matter dominated clouds in the Local Group with distances of hundreds of kiloparsecs. A similar study by Braun & Burton (1999) also claimed that compact and isolated HVCs lie at extragalactic distances. Another popular HVC origin hypothesis is the Galactic fountain model, in which the gas is blown out of the disk by supernovae, cools and then rains back down (see e.g., Houck & Bregman 1990). In this scenario, the fountain gas can rise as high as ~ 10 kpc above the disk (de Avillez 2000).

The previous large-scale all-sky surveys, the Leiden–Argentine–Bonn Galactic H I survey (LAB; Kalberla et al. 2005) and the H I Parkes All-Sky Survey (HIPASS; Barnes et al. 2001) have provided opportunities to study HVCs on a global scale to assist in the understanding of their origin and physical properties (see e.g., Wakker & van Woerden 1991; Putman et al. 2002). LAB covered the entire sky with an angular resolution of $36'$ and a spectral resolution of 1.3 km s^{-1} . HIPASS was conducted with a better angular resolution ($16'$) but lower spectral resolution (18 km s^{-1}). A comprehensive catalog of Southern HVCs based on the HIPASS data was presented in Putman et al. (2002), hereafter P02. The catalog covers the high-velocity H I sky south of declination $+2^\circ$ and within the Local Standard of Rest velocity (V_{LSR}) range of $+500$ to -500 km s^{-1} . It provides the spatial and kinematic distributions as well as the properties of high-velocity clouds. Even though the P02 catalog includes a complete census of HVCs south of declination $+2^\circ$, the nature of the in-scan bandpass calibration technique filtered out some of large-scale structure of the Milky Way and the Magellanic System.

Among HVC complexes, the Magellanic System is the most interesting given that it is the only closest extragalactic gaseous stream to our Galaxy. The Magellanic System consists of a coherent gas stream originating from the Magellanic Clouds (MCs), i.e., Magellanic Stream (MS) and Leading Arm (LA), spanning $\sim 200^\circ$ across the sky (Nidever et al. 2010).

The Magellanic Stream is trailing the MCs and has a complex filamentary structure. On the other hand, the Leading Arm is clumpy and dominated by three distinctive large complexes, namely the LA I, LA II and LA III. The formation of the MS and LA is generally believed to have been caused by the tidal interaction between the Milky Way and Magellanic Clouds. Theoretical models with tidal stripping, gravitational and hydrodynamical interactions can reproduce global observed HI column density and velocity distributions (see e.g., Connors et al. 2006; Mastropietro et al. 2005). However, these models do not provide a satisfactory explanation for the formation mechanism of MS and LA. With the recent Hubble Space Telescope proper motion measurements of the MCs (Kallivayalil et al. 2006a,b), a new orbit for the MCs with a first passage scenario was proposed by Besla et al. (2007). The result is surprising given that the new orbit does not provide sufficient time for tidal and ram-pressure stripping mechanisms to produce the MS (Stanimirović et al. 2008). To circumvent the problem raised by the first passage scenario, Nidever et al. (2008) proposed a new blowout hypothesis. They suggested that the supergiant shells in the dense southeast HI overdensity region are blown out from the Large Magellanic Cloud (LMC) to larger radii where ram-pressure and/or tidal forces can be more easier to strip the gas and form the MS and LA. Nevertheless, recent multi-orbit simulations have reproduced the observed structure of the MS, including bifurcation of the two filaments, whilst remaining consistent with the proper motion data (Diaz & Bekki 2011a,b). However, none of the theoretical models to date have been able to accurately reproduce the observed structure of the LA.

To study the Magellanic System in detail, Brüns et al. (2005) carried out a narrow-band Parkes HI survey. In contrast to HIPASS, which was not designed to accurately measure low-velocity Galactic HI gas, the survey was designed exclusively to study the Magellanic System. The Brüns’ survey has a similar angular resolution and spectral resolution to the Galactic All-Sky Survey (GASS; McClure-Griffiths et al. 2009; Kalberla et al. 2010) (see §2), but with limited sky coverage.

The current work utilizes the GASS data for studying the general distribution and morphological types of HVC in the region of the Magellanic Leading Arm. The GASS data have better sky coverage than the Brüns’ survey and higher spectral resolution than HIPASS. The study of HVCs in the vicinity of the LA gives us clues to understand: (1) the formation of the LA; (2) the physical properties of the HVCs; and most importantly, (3) the role of infalling gas in the context of galaxy evolution and formation. In §2, we describe the GASS data and the procedures for cloud search algorithms. We present the catalog and the general distribution of clouds in §3 and §4. Classification of the clouds and interpretation of the distribution for each group are given in §5. We report on a new population of clouds and extended features of the Magellanic Leading Arm in §6. Finally, we discuss the cloud formation in the gaseous halo in §7 and draw conclusions in §8.

2. DATA

The neutral hydrogen data employed here are from GASS. This survey covers the entire Southern sky to declination $+1^\circ$ and V_{LSR} from -400 to $+500$ km s^{-1} . The data from the GASS second data release¹ have been corrected for stray radiation, have an angular resolution of $\sim 16'$, a brightness temperature (T_B) sensitivity of 57 mK, a channel width of 0.82 km s^{-1} and a spectral resolution of 1 km s^{-1} . For a typical HVC of 15 km s^{-1} line width in our sample, the 1σ HI column density (N_{HI}) sensitivity is 3.5×10^{17} cm^{-2} . We refer the reader to McClure-Griffiths et al. (2009) and Kalberla et al. (2010) for a detailed description of the observing technique and data reduction.

To create a catalog of HVCs in the region of the Magellanic Leading Arm, we extracted a GASS data cube within the area of $-30^\circ \lesssim b \lesssim +40^\circ$ and $240^\circ \lesssim l \lesssim 315^\circ$, and covered the velocity range of 0 to 450 km s^{-1} . Before performing any cloud search algorithm, we examined the data cube and determined the velocity range that solely contain Galactic HI emission, $0 \text{ km s}^{-1} \leq V_{LSR} < 150 \text{ km s}^{-1}$. Beyond this velocity range, there is a mix of Galactic HI emission and possible HI emission that is associated with the MCs. Brüns et al. (2005) analyzed the HVCs in the region of the LA by using different velocity ranges within certain Galactic latitudes. Due to the difficulty in distinguishing the Galactic HI and HI emission originating from the MCs, we deliberately masked out the regions of $-20^\circ \lesssim b \lesssim +20^\circ$ and $l < 310^\circ$ between 150 and 190 km s^{-1} for our analysis. Other small regions of Galactic HI emission in higher velocity channels, as determined by eye, were also masked. An integrated HI column density map of HVCs in the region of the LA over the velocity interval of 150 to 450 km s^{-1} is shown in Figure 1.

2.1. Source Finding

We employed the source finding software, *Duchamp*², developed by Whiting (2012). It is a 3-dimensional source finding software that provides flexibility for the user to control all relevant input parameters. To enhance the detectability of fainter sources, it implements optional noise reduction routines, such as the *à trous* wavelet reconstruction technique (Starck & Murtagh 1994) and the spatial or spectral smoothing routine. A full description of *Duchamp* is given in Whiting (2012). Here we describe the basic flow of the program with the applied input parameters:

¹<http://www.astro.uni-bonn.de/hisurvey/gass/>

²Available at <http://www.atnf.csiro.au/computing/software/duchamp/>

- Spectral channels with Milky Way emission, $0 \text{ km s}^{-1} \leq V_{LSR} < 150 \text{ km s}^{-1}$, were flagged (see §2) and were excluded when performing the search.
- The cube was reconstructed via the *à trous* wavelet reconstruction method. It determined the amount of structures at various scales, and random noise was removed from the cube based on a user defined threshold.
- We did not use the spectral or spatial smoothing to remove the random noise because tests had shown that the *à trous* wavelet reconstruction method yielded a better source detection rate.
- A fixed threshold of $\sim 2\sigma$ above the background noise (57 mK) was specified for the source finding. We did not adopt the auto-threshold determining scheme of *Duchamp*.
- *Duchamp* searched for sources one channel at a time using the defined threshold. Sources were confirmed only if they extend to a minimum of 5 channels in velocity space and 10 pixels spatially.
- Subsequently, detections were compared to earlier detected sources and either combined with a neighboring source or added to the list.

We also performed the source finding using *Clumpfind*. *Clumpfind* is a cloud finding algorithm developed to quantify the fragmentation or clumpiness of molecular clouds (Williams et al. 1994). The routine contours the data with user defined root mean square noise of the observations and interval, then searches for peaks of emission to locate the clumps at each contour level and splits any blended clumps with a friends-of-friends algorithm. We chose to adopt *Duchamp* for this study as it breaks sources into fewer components.

3. CATALOG

We present the basic information of the sources in Table 1. The catalog includes the object identification number in column 1; the designation with a prefix of HVC for high-velocity clouds and GLX for galaxies followed by the Galactic longitude, Galactic latitude and the velocity in the Local Standard of Rest reference frame (V_{LSR}) of the source in column 2; V_{LSR} in column 3; the velocity in the Galactic Standard of Rest reference frame (V_{GSR}), defined by $V_{GSR} = 220 \cos b \sin l + V_{LSR}$; the velocity in the Local Group Standard of Rest reference frame (V_{LGR}), defined by $V_{LGR} = V_{GSR} - 62 \cos l \cos b + 40 \sin l \cos b - 35 \sin b$ (Braun & Burton 1999) in columns 5–6; velocity FWHM in column 6; integrated flux, peak T_B and peak N_{HI} in columns 7–9; semi-major axis, semi-minor axis and position angle in

columns 10–12; warning flag in column 13; and classification in column 14 (see §5). Most of the parameters are derived from *Duchamp*, with the exception of angular sizes and peak H I column density, which are determined independently. Sources that straddle our velocity boundary and masked Milky Way emission boundary are included in the catalog but their physical parameters cannot be determined accurately and are therefore not listed in the table. We present the examples of integrated H I column density maps and LSR velocity maps of individual cloud in Figures 2 and 3.

With the procedures described in §2.1, we found 838 sources with *Duchamp*. False detections caused by background artifacts were eliminated from the initial search. The positions of final detected sources were subsequently examined using the NASA/IPAC Extragalactic Database with a $16'$ search radius to identify any galaxy. The final count includes a total of 407 HVCs and 11 galaxies in the region of the Magellanic Leading Arm. We determined the peak N_{HI} by locating the brightest pixel in the integrated H I column density map of each source. To determine the angular size of the HVCs, we used 2-dimensional Gaussian and elliptical fitting, which gave the semi-major axis, semi-minor axis and position angle. A detailed investigation and discussion of advantages and disadvantages for both fitting methods, applied to molecular cloud catalogs, is given in Kerton et al. (2003). We elect to use the results from the 2-dimensional Gaussian fitting for the catalog. Due to the inaccuracy of the position angle in some cases, caution is needed in interpreting this parameter.

The reliability of *Duchamp* for parametrization of sources has been extensively tested on artificial sources of various parameters by Westmeier et al. (2011). Their tests show that the integrated flux (F_{int}) measured by *Duchamp* is systematically too low for faint sources. To demonstrate how this systematic error affects the integrated flux of real sources found in our catalog, we measured the F_{int} with a better parametrization algorithm. In Figure 4, we show that the ratios of our measured F_{int} to F'_{int} as measured by *Duchamp* as a function of measured *Duchamp* F'_{int} in various bins. Parametrization of large and extended or close kind confused sources is challenging (T. Westmeier, priv communication). Thus, these sources are excluded from the comparison. The red, dotted line is a fit to the data points, which represents the underestimated factor for a given F'_{int} as measured by *Duchamp*. We conclude that *Duchamp* produces accurate measurements of F'_{int} for sources with $F'_{\text{int}} \gtrsim 80 \text{ Jy km s}^{-1}$ in our catalog. We correct all the F'_{int} values measured by *Duchamp* based on the fitting function.

Corrections are not necessary for peak T_{B} (fitted by *Duchamp*) and peak N_{HI} (measured from the column density map). However, small systematic errors in an order of 5–10% of derived values may also be present in these parameters. The *Duchamp* determined velocity FWHM values, however, are generally very accurate (see Figure 8 of Westmeier et al. 2011).

3.1. Comparison with P02 Catalog

Here we compare our catalog to the P02 HVC catalog. The P02 catalog is based on HIPASS data, which have been reprocessed with the MINMED5 method to recover extended emission (Putman 2000). The catalog covers the entire sky in the declination range -90° to $+2^\circ$, and the velocity range of $+90 \text{ km s}^{-1} \lesssim |V_{LSR}| < +500 \text{ km s}^{-1}$. The $|V_{LSR}| < 90 \text{ km s}^{-1}$ limit does not exclude all emission associated with the Milky Way at low Galactic latitudes, and an additional constraint of deviation velocity was applied to their selection criterion. The search was performed via an automated friend-of-friend HVC finding algorithm of de Heij et al. (2002).

In Figure 5, we show a comparison between HVCs from the P02 catalog that fall within our searched GASS survey volume and in our catalog. The total number of identified HVCs in this region is 407 for our catalog and 448 for the P02 catalog. We point out that our catalog includes 27 clouds which straddle our velocity boundary at $V_{LSR} = 150 \text{ km s}^{-1}$ and 71 clouds which extend over to the boundary of masked Milky Way emission region. About 230 HVCs are identified to be the same cloud in the two catalogs. The differences between the catalogs are due to: (a) degrees of breaking up or merging clouds in extended complexes; (b) the superior brightness sensitivity of HIPASS compared to GASS (9 mK per 15 km s^{-1} compared with 15 mK per 15 km s^{-1} in GASS), resulting in more faint sources to be detected in P02; (c) the excellent spectral resolution of GASS has allowed us to resolve narrow-line HVCs in the region, for which the spectral lines would have been smeared out in the case of coarser spectral resolution of HIPASS; (d) GASS has a better baseline coverage at the Galactic plane than HIPASS, resulting in more sources to be detected near the Galactic plane. We present a velocity FWHM distribution of both catalogs in Figure 6. HVCs that straddle our masked Milky Way emission boundaries and galaxies have been excluded in the plot. This figure shows that the majority of HVCs in the P02 catalog possesses larger velocity FWHM ($30\text{--}35 \text{ km s}^{-1}$) than ours ($10\text{--}25 \text{ km s}^{-1}$).

4. General Distribution

The integrated HI column density map of HVCs in the region of the Magellanic Leading Arm shows a significant concentration of HVCs between Galactic longitude 240° to 260° and Galactic latitude -30° to $+0^\circ$ (see Figure 1 and §6). This population appears to be clumpy but has a few larger, more complex clouds ($\sim 3^\circ\text{--}5^\circ$ in angular size). Velocity field maps in the LSR and GSR reference frames, as shown in Figures 7 and 8, indicate large velocity gradients for the LA I and LA II complexes. Faint or thin filamentary structures of complex clouds are not visible in these maps but can be seen in the moment maps of individual

sources (e.g., see Figures 2 and 3). We assume all of these HVCs are originated from the MCs and are associated with the LA due to their close proximity on the sky to the MCs and their similar range of velocities. The following statistical analysis excludes galaxies and objects otherwise flagged in the catalog.

We present the kinematic distributions of HVCs in V_{LSR} , V_{GSR} and V_{LGSR} versus Galactic longitude and latitude in Figures 9 and 10, respectively. A comparison between HVCs in the P02 catalog (black dots) and ours (red dots) is also shown. The main difference is that our catalog only includes sources with $V_{LSR} > 150 \text{ km s}^{-1}$. In the top panel of Figure 9 there are more positive than negative LSR velocity HVCs in the given Galactic longitude range. The overall velocity distribution of all P02 HVCs in Galactic and Local Group reference frames (middle and bottom panels of Figure 9) has nearly equal number of HVCs with positive and negative velocities. The HVCs in our catalog are evenly distributed across the Galactic longitude between 240° and 320° in all reference frames.

The kinematic distributions of our HVCs in Galactic latitude is slightly different than for the HVCs in the P02 catalog. The top panel of Figure 10 shows the lack of identified clouds in the range of $150 \text{ km s}^{-1} < V_{LSR} < 190 \text{ km s}^{-1}$ and $-15^\circ < b < +15^\circ$ in our catalog. The lack of clouds in this region is caused by the way we constructed the data cube by deliberately masking out most of the emission in this velocity range to avoid any contamination from the Galactic HI emission (see §2). There is a lack of clouds at higher Galactic latitude as the velocity increases in all reference frames.

In Figure 11, we show histograms of V_{LSR} , V_{GSR} , Galactic longitude and latitude (from top to bottom panels). The median V_{LSR} and V_{GSR} for the HVCs in the catalog are 232 km s^{-1} and 42 km s^{-1} , respectively, which is consistent with the mean radial velocity of the LA (Brüns et al. 2005). We find that the number of clouds declines gradually as V_{LSR} increases above 200 km s^{-1} . Nearly the same number of clouds per 5° bin is found between Galactic longitude 250° and 300° (third panel). The total number of clouds below the Galactic plane outnumbers those above the Galactic plane, with a large fraction agglomerated between Galactic latitude -25° and -10° (bottom panel), where the region is closer to the LMC.

In Figure 12, we show the distribution function of peak HI column density, which can be described by a power law: $f(N_{\text{HI}}) \propto N_{\text{HI}}^\alpha$. The distribution shows that high column density clouds are rare. The turn-over at the low column density end of the distribution indicates that the population is limited by the survey sensitivity ($1\sigma = 3.5 \times 10^{17} \text{ cm}^{-2}$). A linear function was fitted in the log–log space and a negative slope of -1.0 was determined. This yields the final form of the distribution function as $f(N_{\text{HI}}) \propto N_{\text{HI}}^{-2.0}$.

5. High-Velocity Cloud Morphological Classification

Different shapes of HVCs have been identified in the past, head-tail clouds in particular have been studied extensively (see e.g., Brüns et al. 2000; Westmeier et al. 2005; Putman et al. 2011). Examining the integrated H I column density and velocity field maps of each cloud, we can classify the HVCs into 5 groups: (1) clouds with head-tail structure and with velocity gradient (HT); (2) clouds with head-tail structure but without velocity gradient (:HT); (3) bow-shock shaped clouds (B); (4) symmetric clouds (S); and (5) irregular/complex clouds (IC). In Figure 13, we show different morphological type of clouds in our catalog. An analysis of groups 1–4 is given in the following subsections.

5.1. Head-Tail Clouds

Traditionally, a head-tail cloud is defined as a cloud which appears to be cometary with a compressed head trailed by a relatively diffuse tail; and a clear column density gradient is visible (Brüns et al. 2000). In this study, we find that some head-tail clouds consist of an additional clump of diffuse gas or have a kink in the tail, slightly more complex than the traditional head-tail clouds. This structure suggests a fraction of the gas is being ripped off from the main condensation when it interacts with the surrounding halo gas.

Among the head-tail clouds, some show a velocity gradient, which is generally also associated with a column density gradient. Such a velocity gradient is another possible indicator for the detection of distortion caused by the interaction between clouds and an ambient medium (e.g., see PSM11; Brüns et al. 2000). Detection of a velocity gradient strongly depends on the spectral resolution of the data. Because of the high spectral resolution of GASS, in contrast to HIPASS, it is feasible to measure velocity gradient in addition to the H I column density gradient when classifying head-tail clouds. We divide the head-tail clouds into two types (group 1 & 2) and analyze them separately.

The total number of head-tail clouds is 100 ($\sim 25\%$ of the sample), with typical head and tail column density different by a factor of 5 (typically $\Delta N_{\text{HI}} \sim 4 \times 10^{18} \text{ cm}^{-2}$). 60% (61/100) of the head-tail clouds show a clear velocity gradient. A wide range of velocity differences between the head and tail ($\sim 5\text{--}25 \text{ km s}^{-1}$) is detected. We find that this particular group of head-tail clouds with velocity gradient consists of two subgroups, with the velocity of the head either leading (pHT) or lagging (nHT) the tail. The number in the subgroups is about the same, 30 and 31, respectively.

In Figure 14, we show the peak H I column density distributions of head-tail clouds with velocity gradient (top panel) and without velocity gradient (bottom panel) in the region

of the LA. The pointing direction of the head-tail clouds is also presented, with the head and tail having been enlarged for better visibility. As discussed in §3, the accuracy of the position angle is subject to the fitting methods and complexity of the cloud shape. To better represent the pointing direction of the clouds, we visually inspected each head-tail cloud and manually adjusted the Gaussian fit position angle whenever necessary.

The head-tail clouds appear to be pointing in a random direction regardless whether they belong to group 1 or group 2. In contrast, the study by PSM11 found that the majority of head-tail clouds in the region of the Leading Arm point in the general direction of the North Galactic Pole, consistent with the general motion of the Magellanic System. The different conclusions may partly be due to the differences in selection criteria: (a) the velocity gradient is not well measured in PSM11; (b) only compact, isolated HVCs (CHVCs) are searched for head-tail structure in PSM11; (c) the selection of head-tail clouds is a subjective process. We have about factor of two more head-tail clouds with velocity gradient than PSM11 in the same region. The implication of this random motion for the formation of the LA and its interaction with the Galactic halo will be discussed in §7.

Examining the peak H I column density distributions of both head-tail groups, we find that they populate the entire range of H I column densities and are spread over the entire region. The distribution in V_{LSR} for both groups is shown in Figures 15 and 16, in which a dichotomy is found above and below the Galactic plane. Above the Galactic plane, majority of the HT and :HT clouds possess $V_{LSR} < 225 \text{ km s}^{-1}$. Below the Galactic plane, it is populated by HT clouds with a wide range of V_{LSR} .

The distributions of peak H I column density and velocity FWHM of these two head-tail groups as compared to the general population of HVCs in this study are presented in Figure 17. The black, blue and red histograms represent all HVCs, head-tail clouds with velocity gradient (HT) and head-tail clouds without velocity gradient (:HT) clouds, respectively. The peak H I column density distributions are fairly similar in the cases of all HVCs and HT clouds, with the majority in the range of $18.4 < \log(N_{\text{HI}}/\text{cm}^{-2}) < 18.6$ (top panel). This result is different than the recent study by PSM11, where the majority of head-tail clouds in their sample possess $\log N_{\text{HI}} > 19.0$. This is a factor of 2.5 higher in column density than those found in our sample. The difference is caused by the overall peak H I column density distribution and number of detected narrow line width clouds between P02 and our catalog. The peak H I column density distribution for :HT clouds is rather flat, most likely because of the small sample size. The velocity FWHM distributions are asymmetric with a peak at 22 km s^{-1} in all cases (bottom panel). Both velocity FWHM distributions of HT and :HT clouds extend out to $\sim 40 \text{ km s}^{-1}$.

To analyze the two subgroups of head-tail clouds with velocity gradient (i.e., pHT and

nHT), we plot them with different symbols in Figure 18. The plus and square symbols represent the pHT and nHT clouds, respectively. There are approximately equal numbers of pHT clouds and nHT clouds above and below the Galactic plane for both the peak HI column density and V_{LSR} distributions. As for the distribution of V_{LSR} (bottom panel), pHT clouds possess slightly lower V_{LSR} ($< 200 \text{ km s}^{-1}$) than nHT clouds ($< 250 \text{ km s}^{-1}$) above the Galactic plane. Below the Galactic plane, pHT clouds are evenly distributed across the range of V_{LSR} , and nHT clouds dominate at $V_{LSR} > 250 \text{ km s}^{-1}$.

5.2. Symmetric and Bow-Shock Clouds

The bow-shock shaped cloud is characterized by a dense core with two deflected gas wings, which have lower column density than the core. The presence of this type of cloud suggests ram-pressure interaction with the ambient medium. On the other hand, symmetric clouds do not exhibit any morphological signs of disturbance. We note, however, that a head-tail cloud aligned with the major axis along the line of sight would also appear as a symmetric cloud.

In Figure 19, we show the distributions of symmetric (diamonds) and bow-shock shaped (crosses) clouds in peak HI column density and V_{LSR} . There are only few high HI column density ($> 10^{18} \text{ cm}^{-2}$) symmetric clouds are found above the Galactic plane. Otherwise, they cover a wide range of N_{HI} in the region of the LA. The majority of these clouds fall between 225 km s^{-1} and 340 km s^{-1} below the Galactic plane and less than 250 km s^{-1} above the Galactic plane. With a small sample of bow-shock shaped clouds, we conclude that the typical bow-shock shaped cloud has $N_{\text{HI}} \sim 0.2 - 1 \times 10^{19} \text{ cm}^{-2}$ and velocity less than 250 km s^{-1} .

34% (23/69) of symmetric clouds also exhibit a velocity gradient. It is not unusual to detect velocity gradient among symmetric clouds given that it can be caused by several effects. For example, the velocity gradient is detected when there is an angle between the HVC velocity vector and the line of sight; and in rare cases when two or more HVCs are superimposed on the same line of sight with comparable group velocities (Brüns et al. 2000). There is no preferred direction of the velocity gradient for symmetric clouds in our catalog.

6. A NEW CLOUD POPULATION AND EXTENDED FEATURES OF THE MAGELLANIC LEADING ARM

With the all-sky coverage of GASS, we have uncovered new extended features of the Magellanic Leading Arm. In Figure 20, we show the relative position of the LA I, LA II and LA III (top figures) and individual LA complexes as identified by *Duchamp* (bottom subfigures). The red boxes highlight the extended features that were not detected in Brüns’ survey. The extended feature in LA I has been seen in other all-sky HVCs map (see e.g., Putman et al. 2002). It was not detected in the Brüns’ survey due to its longitude coverage cutoff at 310° near the LA I region.

The other extended feature seen in LA III is new. This feature consists of clumps connected by diffuse, low H I column density filaments. The most interesting part about this extended feature is what appears to be a “bridge” connecting the LA II (see the arrow in top figure). The velocity map of this extended feature also shows similar velocity between LA I and LA III near the “bridge”.

Lastly, we report a new population of clouds, named LA IV, that is located South of the Galactic plane and to the north-west of the LMC. The median V_{LSR} of LA IV is $\sim +260 \text{ km s}^{-1}$. The blue and dashed lines mark the estimated boundary and extended boundary of the population in the top left panel of Figure 20, respectively. The morphology of LA IV is different from its counterparts, the LA I, II and III complexes. It is formed by a stream of cloudlets, and the majority of which are head-tail and symmetric clouds. This feature should be incorporated into future theoretical modeling. The top right panel shows a schematic diagram of the LA features.

7. Discussion

The morphology of HVCs provides an important clue in studying the interaction between the neutral hydrogen gas and the ambient medium in the Galactic halo. Head-tail clouds are a classic example of cloud disruption via ram-pressure stripping when moving through the halo medium. They are relatively common as compared to the other morphological types. Such interaction commonly results in Kelvin-Helmholtz and thermal instabilities, and ultimately cloud fragmentation and evaporation (Konz et al. 2002).

Parameters such as the cloud size, halo and cloud densities have been shown to govern cloud stability in 3-dimensional hydrodynamical simulations (see e.g., Heitsch & Putman 2009; Quilis & Moore 2001; hereafter HP09 and QM01, respectively). In the QM01 models, pure gas and extragalactic dark-matter dominated HVCs with various gas densities, velocities

and temperatures were investigated. They found that a tail with $N_{\text{HI}} \geq 10^{19} \text{ cm}^{-2}$ appears when the external medium exceeds the density of 10^{-4} cm^{-3} , although a weak, faint tail with $N_{\text{HI}} \sim 10^{18} \text{ cm}^{-2}$ also becomes visible when the density of the external medium reaches $2 \times 10^{-5} \text{ cm}^{-3}$. The setup of the HP09 simulations was slightly different from QM01. They took into account the heating by an ultraviolet radiation field and metallicity-based cooling mechanisms. Various halo density profiles, cloud masses and velocities were tested for their wind-tunnel and free-fall models. The wind-tunnel model is best described as exposing the HVC to a wind with constant velocity and density. The free-fall model follows the trajectory of the HVC through an isothermal hydrostatic halo toward the disk. While both studies only consider clouds at lower z (within 10 kpc for the HP09 models), and hence might not be suitable to explain the formation and evolution of HVCs originating from the Magellanic Clouds, it is quite interesting to note that the simulations have successfully simulated prominent head-tail clouds even with kinks or multiple cores that are reminiscent of the observational structure of head-tail clouds in this study. The simulated timescale for the cloud disruption strongly depends on the physical conditions in the cloud and its interacting environment. Most head-tail clouds with high velocity are disrupted within 10 kpc and 100 Myr in the HP09 model but tail disruption can last as long as $\sim 10^9$ yr in QM01 model after which the H I column density drops below the observational threshold.

The presence of a large number of head-tail clouds in the region of the Magellanic Leading Arm as compared to the Magellanic Stream is somewhat curious (see PSM11 and Stanimirović et al. 2008). Studies of filaments along the MS have shown that they are dominated by spherical shaped clouds and are absent of elongated or head-tail clouds (Stanimirović et al. 2008). This may imply that ram-pressure stripping is a more important factor than gravitational force for producing the morphological features of the LA. The Leading Arm complexes are similar to head-tail clouds on a large scale. The directionality of their head and tail suggests that they are moving toward higher Galactic latitudes. The velocity gradient shows that the velocity at the head is slower than the tail in LA I and II (see Figure 7). This kind of velocity gradient is expected when the head of the cloud is decelerated while moving through the ambient medium.

Assuming that all small HVCs in the region of the Magellanic Leading Arm (excluding cloudlets that form part of the LA IV) are fragments from the LA complexes due to cloud disruption, the directionality of the head-tail clouds should follow the direction of motion of the LA. However, this is not what we observed either for the head-tail clouds with or without velocity gradient (as mentioned in §5.1; see also Figure 14). The pointing direction of the head-tail clouds is random which suggests that turbulence in the medium must be at play. According to Audit & Hennebelle (2005), this scenario can be generated when the incoming warm neutral gas collides with the hotter ambient medium and creates a thermally unstable

region. If the flow is weakly turbulent, part of the warm gas condenses into cold gas, and any thermally unstable cold gas will continue to fragment until thermal equilibrium is achieved. In the case of a strongly turbulent incoming flow, which is the case for the interaction between the LA and the Milky Way halo medium (based on the velocity of the gas stream), the fragmented clouds should appear distorted and irregular. Strong turbulence also promotes the occurrence of fragmentation for the thermally unstable clouds, and subsequently, more small, cold clouds with lower density. This scenario appears to agree with the properties of HVCs in the region of the LA.

In addition to the ram-pressure stripping mechanism mentioned above, distance must have an effect on the morphology because the HI gas can interact with different ambient medium in different regions of the Galactic halo. With the exception of the LMC and SMC distances (50 and 60 kpc, respectively), distances to the LA and MS are hard to determine. According to the tidal models, the MS is further away from the Galactic plane than the MCs and the LA, with distances of 50–100 kpc at its tip (Yoshizawa & Noguchi 2003; Connors et al. 2006). An empirical study of filaments near the tip of the MS estimated a distance of 70 kpc, which is in agreement with the tidal models (Stanimirović et al. 2008).

The LA is at an approximate kinematic distance of 21 kpc (McClure-Griffiths et al. 2008), based on the evidence of interaction between the LA I with the Galactic disk gas. This distance is smaller than the estimate due to cloud disruption timescale, in which the gas stream from the MCs is not expected to reach the disk in the form of HI clouds (Heitsch & Putman 2009). Simulations also put the distance of the LA to ~ 50 kpc (see Figure 4 of Diaz & Bekki 2011b), although addition of ram-pressure stripping could result in a closer distance (Connors et al. 2006).

In §5.1, we presented the dichotomy in radial velocity for the head-tail and symmetric HVCs above and below the Galactic plane (see Figures 15 and 19), in which the HVCs below the Galactic plane possess lower V_{LSR} than above the Galactic plane. Such dichotomy (or gradient as a function of Galactic latitude) is also seen in simulations, although with an offset between the model and the observational data (see Figure 7 of Diaz & Bekki 2011b). Since we are only interested in the real distortion due to interaction of the cloud with the ambient medium, we will only consider the head-tail clouds with velocity gradient for the rest of this discussion.

If we assume that all LA HVCs are traveling along the same orbit as the MC's, we can use knowledge of the MC's total velocity and vector components to estimate the tangential velocity (V_t) of the HVCs from their measured radial velocities in the GSR frame. Hence, we can translate the median V_{GSR} of HT clouds above and below the Galactic plane into their associated tangential velocities (V_t) based on the relative fractions of V_t and V_{GSR} of the MCs

(LMC: $V_t = 367 \text{ km s}^{-1}$, $V_{GSR} = 89 \text{ km s}^{-1}$; SMC: $V_t = 301 \text{ km s}^{-1}$, $V_{GSR} = 23 \text{ km s}^{-1}$; Kallivayalil et al. 2006a). With the median V_{GSR} of -7 and 54 km s^{-1} for clouds above and below the Galactic plane, the estimated tangential velocities are 270 km s^{-1} and 330 km s^{-1} , respectively. While the V_t difference is small, the dichotomy suggests that the HT clouds move through a different ambient medium. The relatively low velocity for clouds above the Galactic plane suggests that they may have moved through a denser ambient medium that imparted a drag force on the clouds. Under this assumption we can estimate the mean density of the halo region ($n_h(z)$) that the clouds move through,

$$C_D f_c n_h(z) = \frac{2N_{HI}g(z)}{v^2} \quad (1)$$

(Benjamin & Danly 1997), where C_D is the drag coefficient, $f_c = N_{HI}/(N_{HI} + N_{HII})$ is cloud neutral fraction, $g(z)$ is the gravitational acceleration, N_{HI} is the total H I column density of the cloud and the v is velocity of cloud. We assume that the total H I column density of a typical head-tail cloud is 10^{19} cm^{-2} , the drag coefficient and cloud neutral fraction are 1.0, and the gravitational acceleration is constant ($0.2 \times 10^{-8} \text{ cm s}^{-2}$) beyond 10 kpc (Wolfire et al. 1995) for determining the mean halo densities. For the velocities above and below the Galactic plane of 270 km s^{-1} and 330 km s^{-1} , we obtain $n_h = 5.4 \times 10^{-5}$ and $3.7 \times 10^{-5} \text{ cm}^{-3}$, respectively. We note that the calculation is sensitive to the adopted cloud H I column density. Nevertheless, while the halo density is poorly known beyond 10 kpc, this exercise demonstrates that velocity dichotomy can be produced under different halo density environments, and hence implies different distances of the clouds. Based on the hot halo model of Wolfire et al. (1995) (see Figure 1 of Benjamin & Danly 1997), the halo density starts to decrease gradually at ~ 3.5 kpc. If we assume that this trend continues further out in z , taking the approximate n_h of $4.7 \times 10^{-5} \text{ cm}^{-3}$, the extrapolated distance is 30 ± 5 kpc. Considering the large uncertainty, this is consistent with a kinematic distance of ~ 20 kpc for the LA.

Finally, with this measurement of the distance of the LA, we suggest that fragmentation is not the only mechanism that produces the small clouds in the region. The cloud fragments with lower z would experience increased background pressure which would increase the cooling rate. This would result in reforming of cold H I clouds, as seen under the free-fall model of HP09.

8. Summary and Conclusions

We have produced a catalog of high velocity clouds in the region of the Magellanic Leading Arm from Parkes Galactic All-Sky Survey data, using the cloud search algorithm

Duchamp. We used *Duchamp* to parametrize cloud properties including position, velocity and velocity FWHM. We determined the angular size of sources via 2-dimensional Gaussian fitting and peak H I column density via searching the brightest pixel in the integrated maps. Comparison between our HVC catalog with that of Putman et al. (2002) in the same region and velocity range shows that the high spectral resolution of GASS allows us to recover clouds with narrow-line widths. The total number of detected HVCs is 448 for P02 catalog and 407 for our catalog. The combined catalog contains ~ 625 unique clouds.

We have presented the general distribution of HVCs in the catalog. The kinematic distributions with respect to Galactic longitude and latitude are generally consistent with the findings in P02. A trend of decreasing number of clouds from higher to lower Galactic latitude as velocity increases in all velocity reference frames was found. A morphological classification of clouds was presented, and distributions of each type were discussed.

An extended feature in the LA I complex that was not covered in the detailed study of the Magellanic System by Brüns et al. (2005) was noted. A new population of clouds that forms the LA IV and an extended feature that forms a diffuse “bridge” connecting the LA II and III complexes were also discovered. The discovery of the LA III extended feature demonstrates the importance of brightness temperature sensitivity and spectral resolution for an all-sky survey. Simulations have yet to reproduce this feature of LA.

The most significant result in this study was the detection of a large number of head-tail clouds in the region of the LA as compared to the MS, suggesting that ram-pressure stripping is relatively more important than gravitational forces for the morphology and formation of the LA. The LA I and II themselves are large head-tail clouds, which are moving toward higher Galactic latitudes and both show a large velocity gradient, with the head being lower than the tail. We found that there was no preferred pointing direction for the small head-tail clouds. This suggests a scenario where the clouds are produced in a turbulent flow where incoming warm neutral gas collides with the hot halo ISM. The cloud morphologies are strongly correlated to the degree of turbulence in the ISM. The presence of strong turbulence is probably the cause for the observed morphologies and properties of clouds in the region.

A dichotomy in velocity for the head-tail and symmetric HVCs above and below the Galactic plane was found. The lower tangential velocity of head-tail clouds above the Galactic plane may be related to drag induced by movement through a denser medium. Using the typical H I column density of cloud and tangential velocities above and below the Galactic plane, we estimated halo density of $4.7 \times 10^{-5} \text{ cm}^{-3}$. Finally, the clouds distance is derived to be 30 ± 5 kpc, which is consistent with the kinematic distance of 21 kpc reported by McClure-Griffiths et al. (2008).

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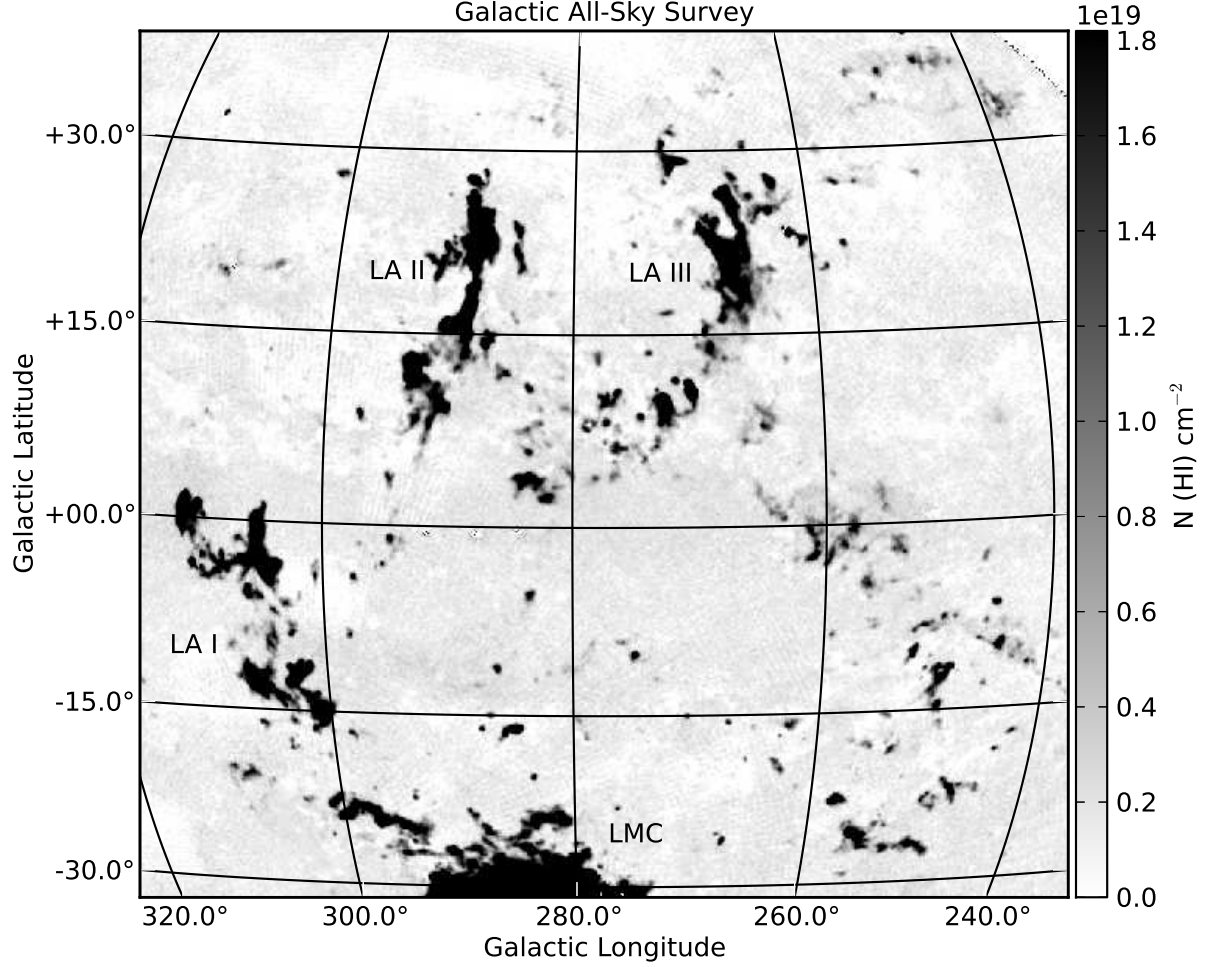


Fig. 1.— The integrated HI column density map of GASS in the region of the Magellanic Leading Arm. The HI column density scale is 0 to $1.8 \times 10^{19} \text{ cm}^{-2}$. Locations of the Leading Arm complexes I, II, III and the Large Magellanic Cloud are labeled.

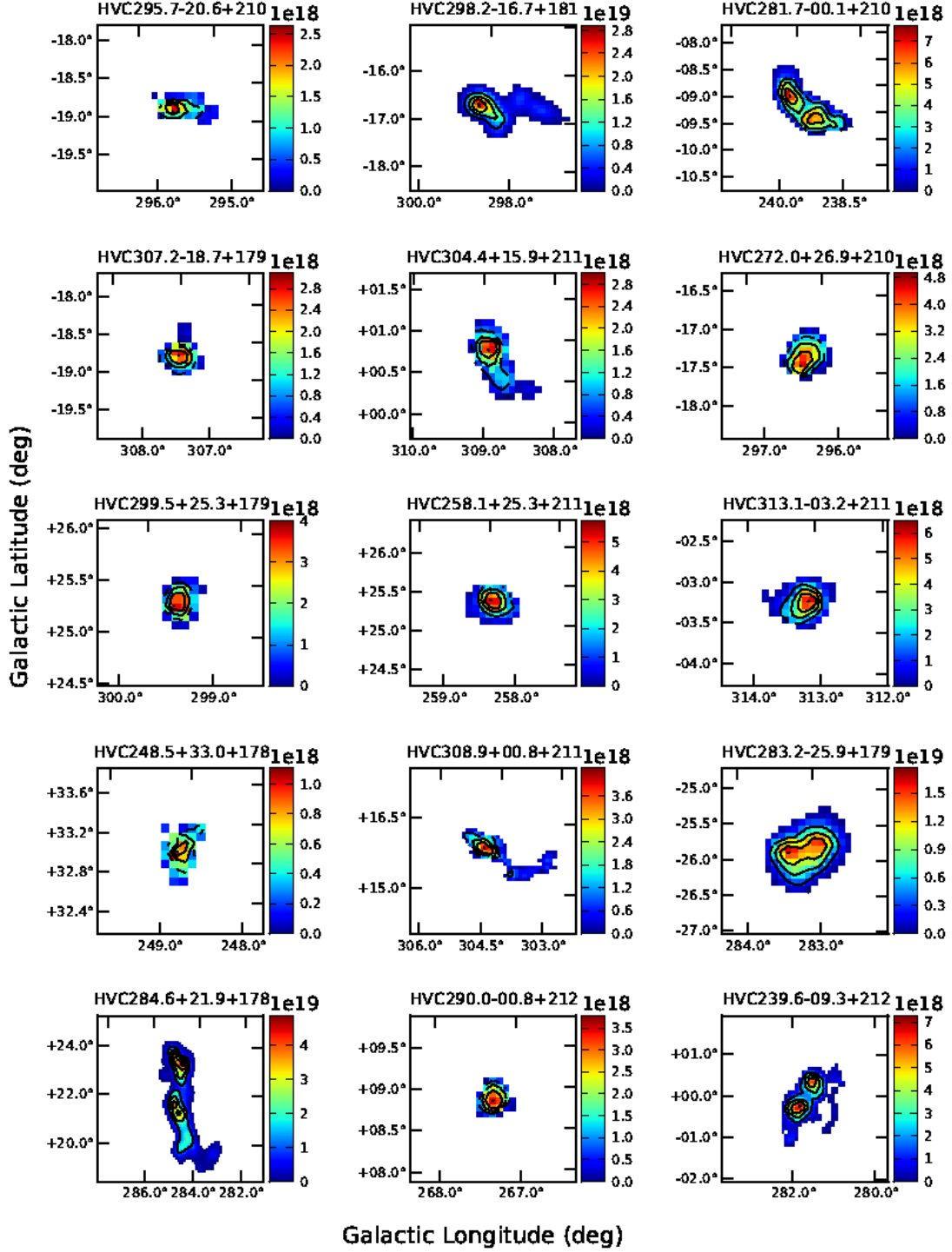


Fig. 2.— Examples of integrated H I column density maps of individual sources. Contours and colors representing the H I column density scale are shown.

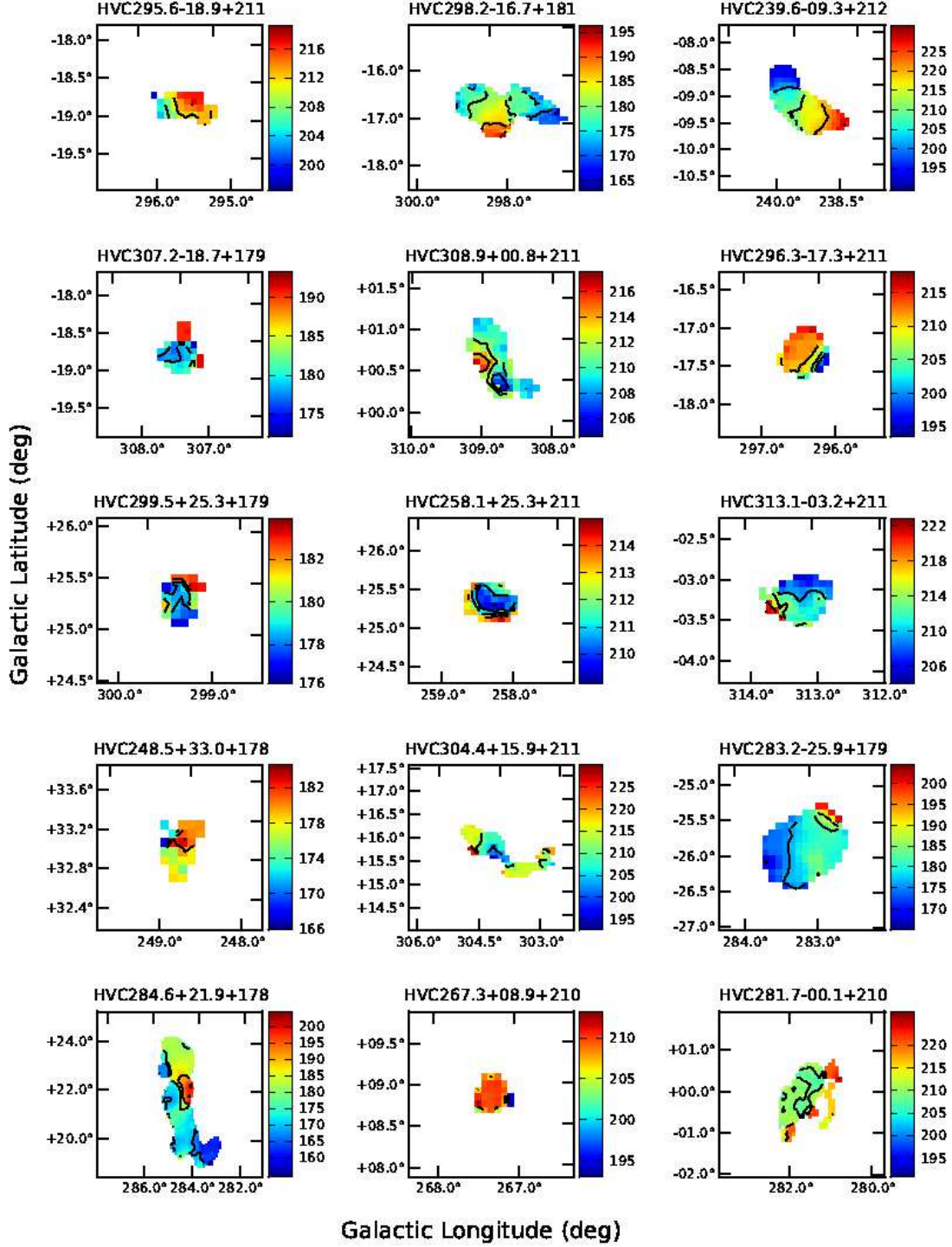


Fig. 3.— Examples of velocity field maps of individual sources. Contours and colors representing the LSR velocity are shown.

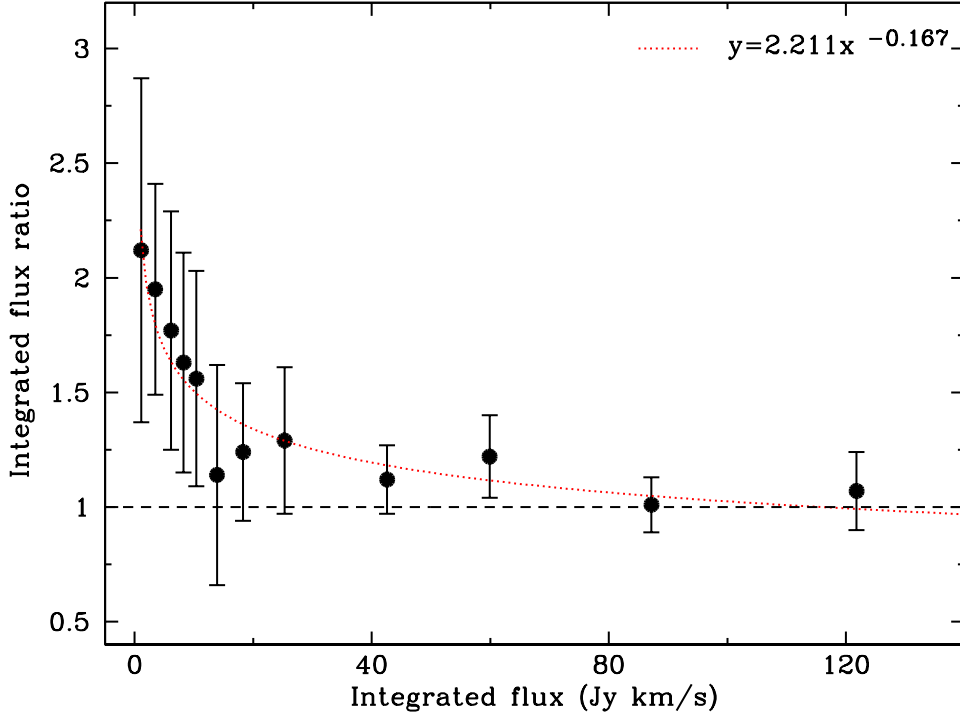


Fig. 4.— Ratio of “true” integrated flux (F_{int}) to the integrated flux (F'_{int}) measured by *Duchamp* as a function F'_{int} . The red dotted line is the fit to the data points, which represents our estimated correction to the *Duchamp* values.

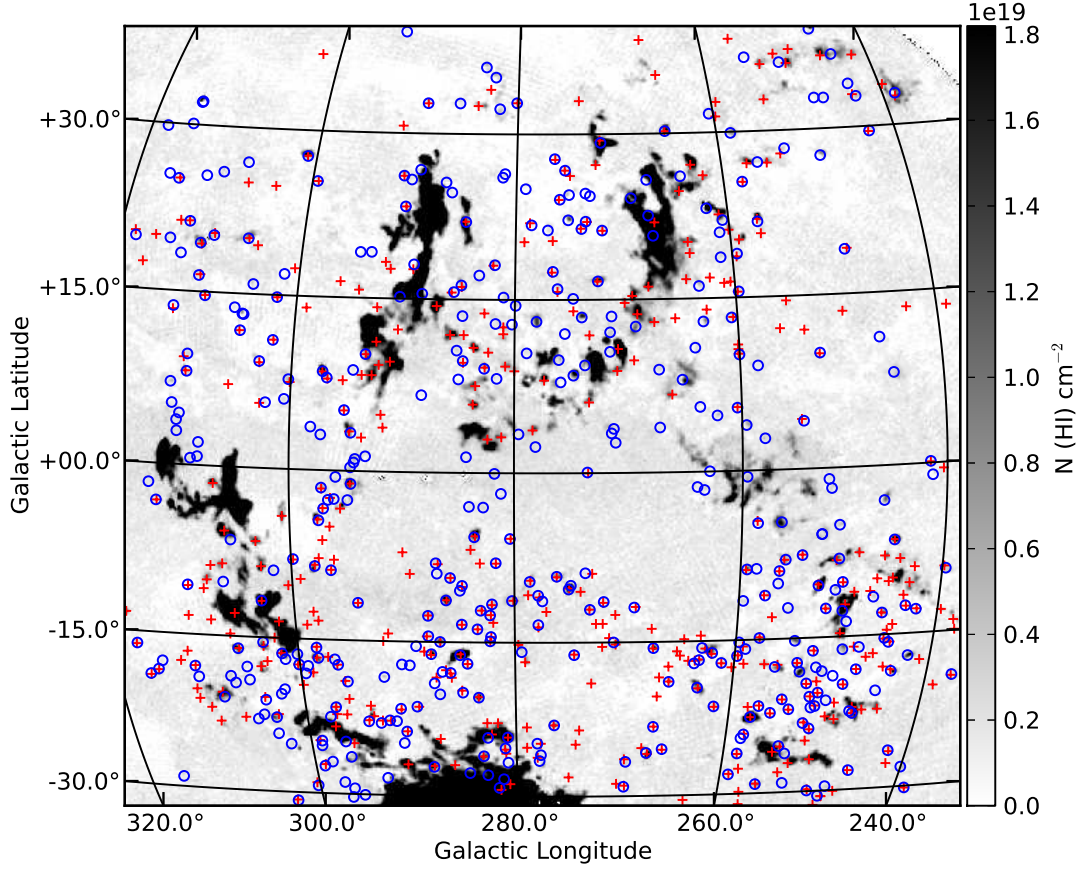


Fig. 5.— On-sky distribution of the 418 sources detected by *Duchamp* (blue circles) and the 448 sources detected by Putman et al. (2002) (red pluses) in the region of the Leading Arm. The integrated H I column density map of Figure 1 is shown. The sources from Putman et al. (2002) are within the same velocity range as the catalog presented in this paper. Comparison between the two catalogs is discussed in §3.1.

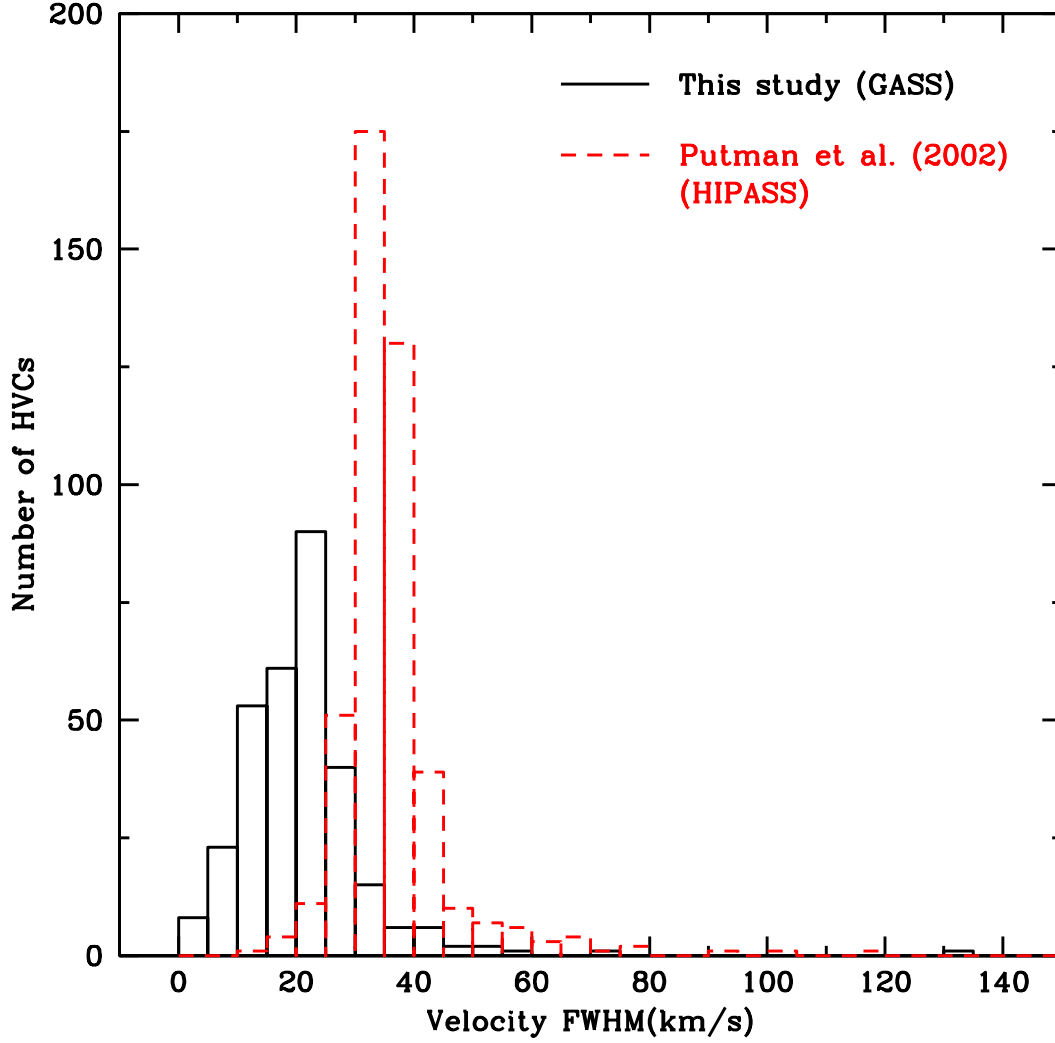


Fig. 6.— Histograms of velocity FWHM of HVCs in P02 (dashed line) and this study (solid line). Excluded from the plot are: 37 clouds that extend below $V_{LSR} = 150 \text{ km s}^{-1}$; 71 clouds that extend into the masked Milky Way emission boundary; and galaxies. A larger number of narrow-line width HVCs are recovered in this study as compared to P02. The difference is mainly due to the higher spectral resolution of GASS.

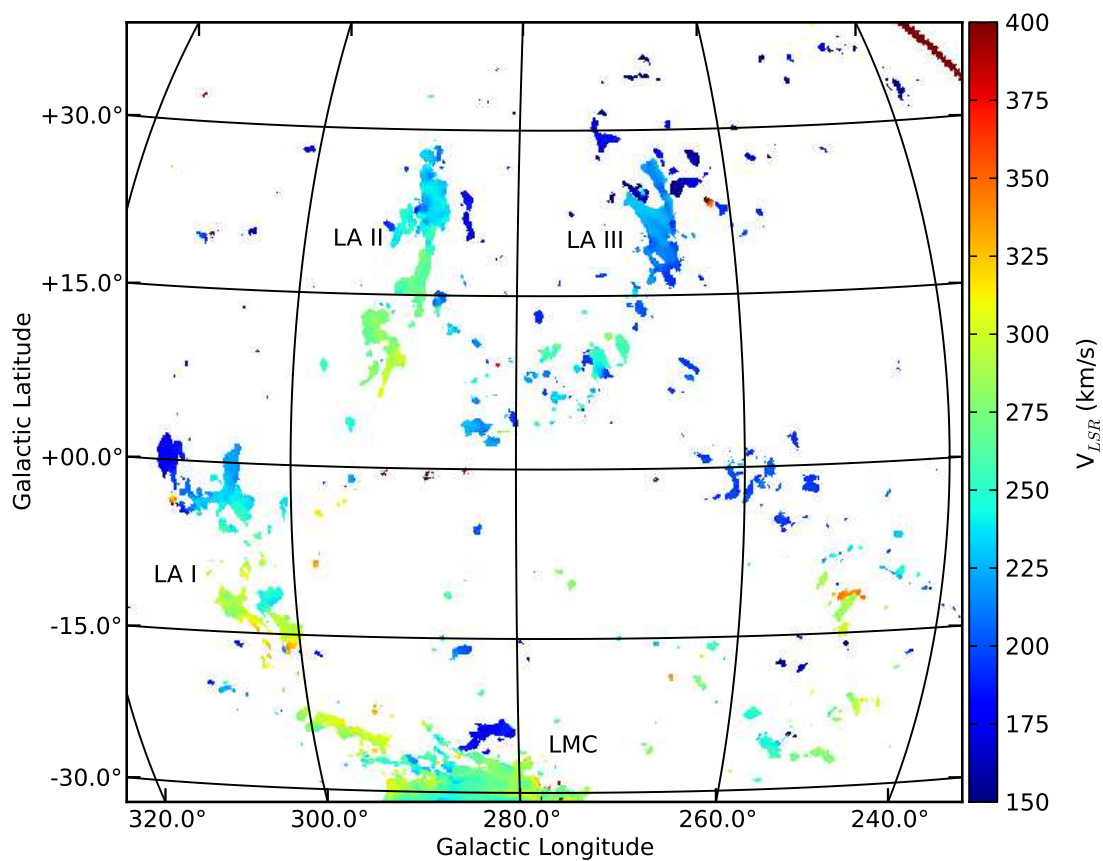


Fig. 7.— The velocity field map (first moment map) in the LSR velocity reference frame. The color bar represents the velocity range from 150 to 400 km s⁻¹. The Leading Arm complexes and Large Magellanic Cloud are labeled.

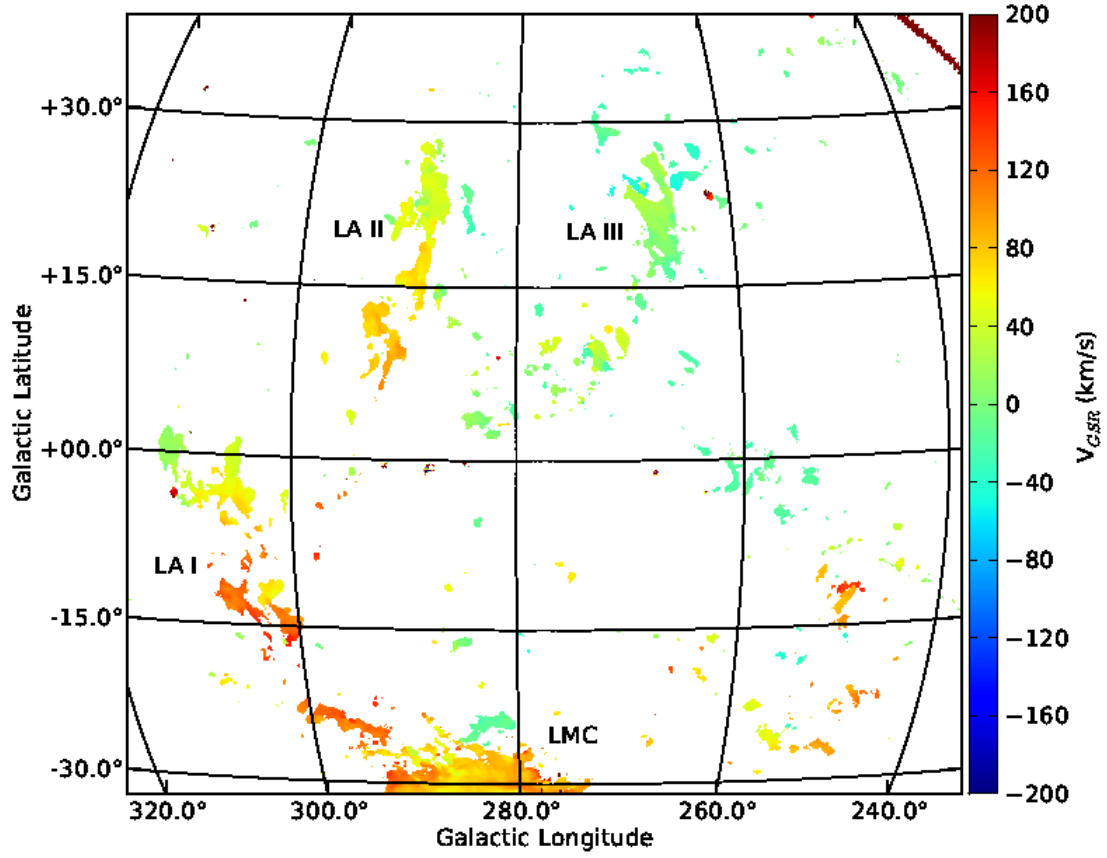


Fig. 8.— Same as Figure 7, except in the GSR velocity reference frame with a velocity range of -200 to $+200$ km s^{-1} .

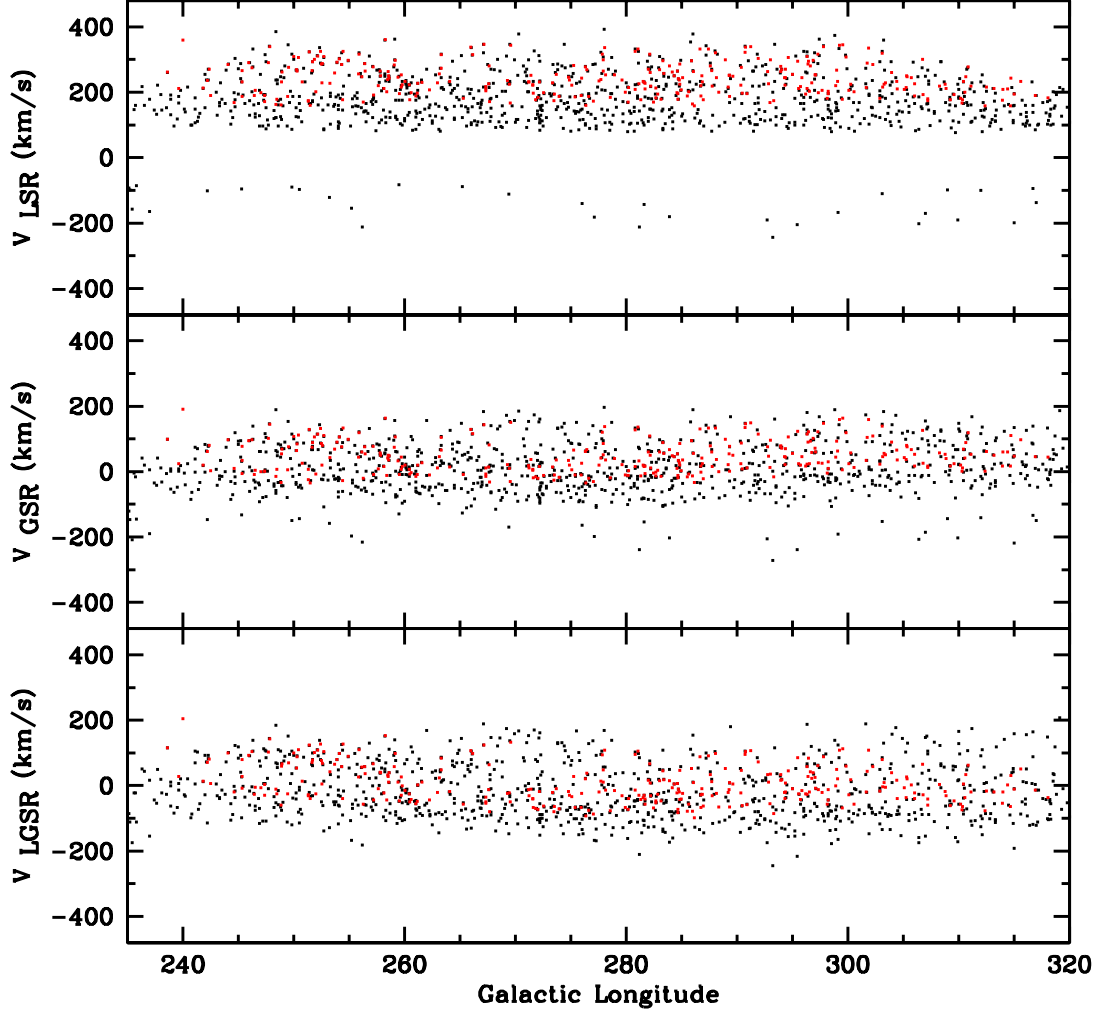


Fig. 9.— Kinematic distributions of HVCs in the V_{LSR} , V_{GSR} and V_{LGSR} reference frames versus Galactic longitude (from top to bottom). The black and red dots represent HVCs in P02 and our catalog, respectively. Excluded from the plot are: 37 clouds that extend below $V_{LSR} = 150 \text{ km s}^{-1}$; 71 clouds that extend into the masked Milky Way emission boundary; and galaxies.

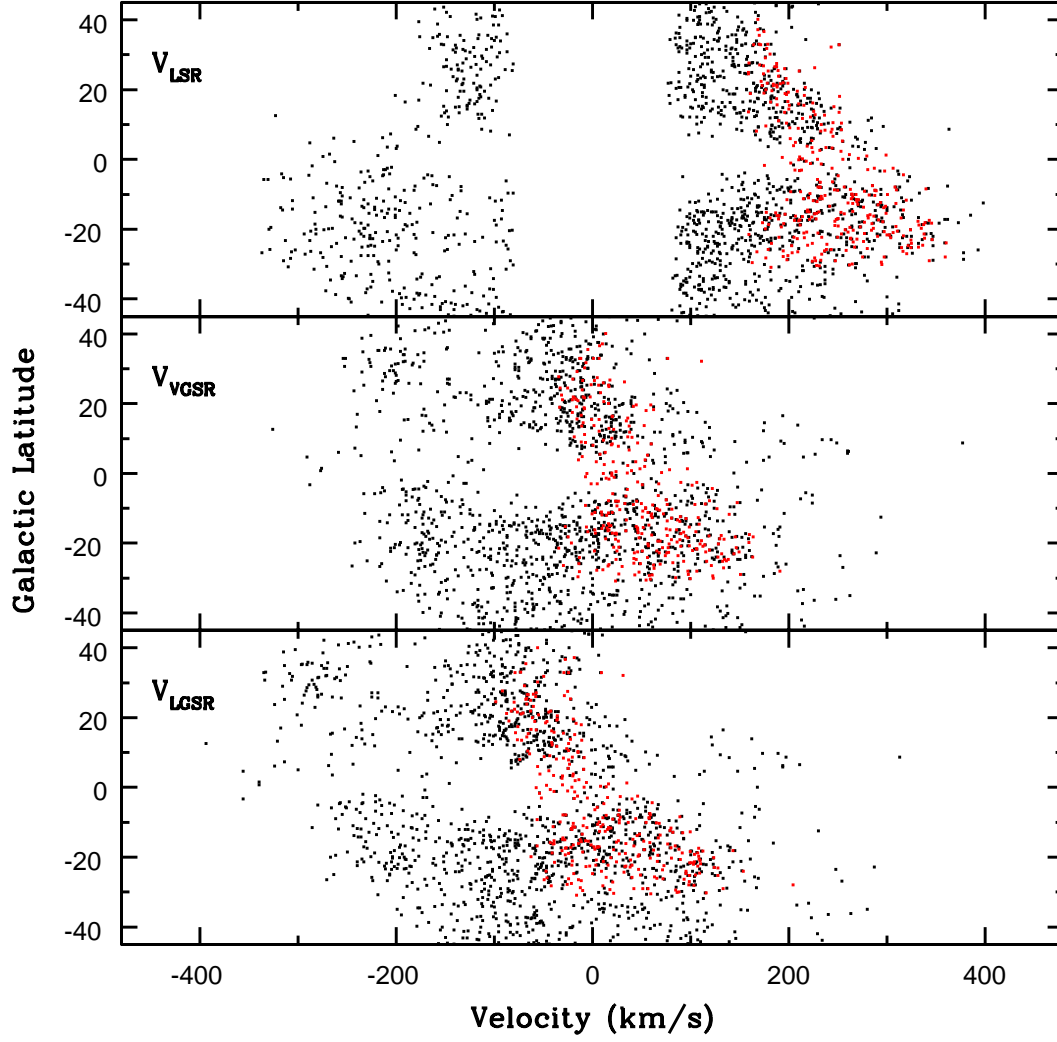


Fig. 10.— Same as Figure 9, except showing velocities versus Galactic latitude.

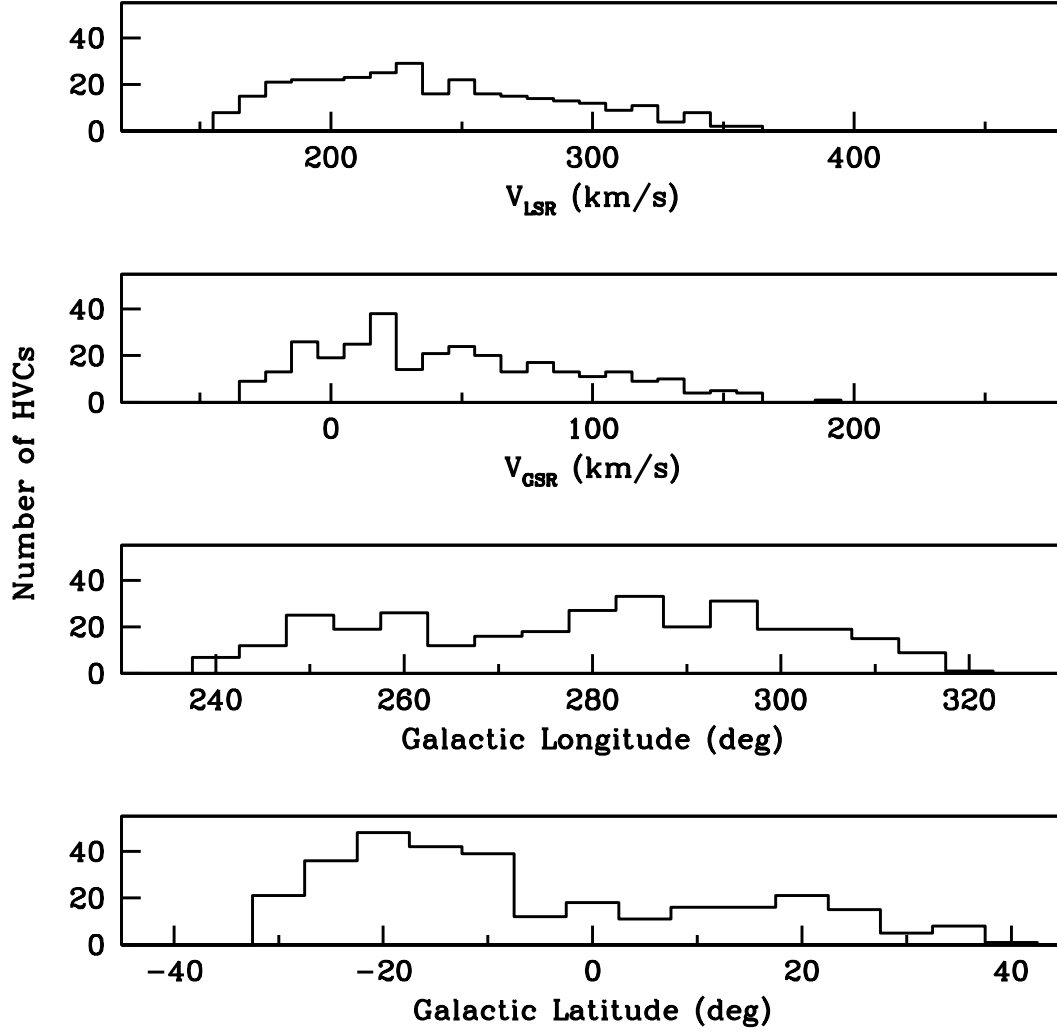


Fig. 11.— Histograms of V_{LSR} , V_{GSR} , Galactic longitude and Galactic latitude of HVCs identified in the GASS data, from top to bottom, respectively. Excluded from the plot are: 37 clouds that extend below $V_{LSR} = 150 \text{ km s}^{-1}$; 71 clouds that extend into the masked Milky Way emission boundary; and galaxies.

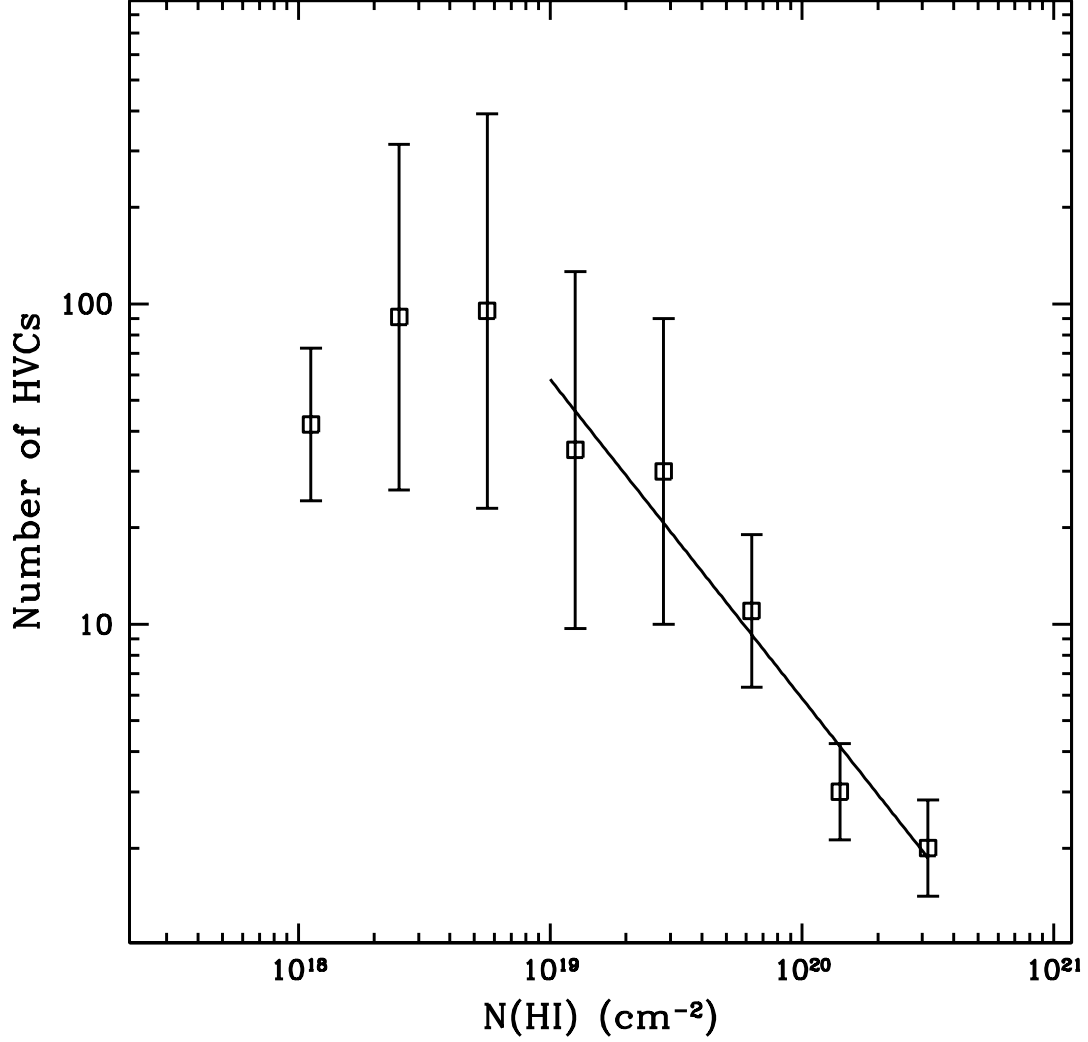


Fig. 12.— The peak HI column density distribution of HVCs in our catalog. A slope of -1.0 is derived from least square fitting of the data points above 10^{19} cm^{-2} in the log-log plane, which corresponds to distribution function, $f(N_{\text{HI}}) \propto N_{\text{HI}}^{-2.0}$. Excluded from the plot are: 37 clouds that extend below $V_{\text{LSR}} = 150 \text{ km s}^{-1}$; 71 clouds that extend into the masked Milky Way emission boundary; and galaxies.

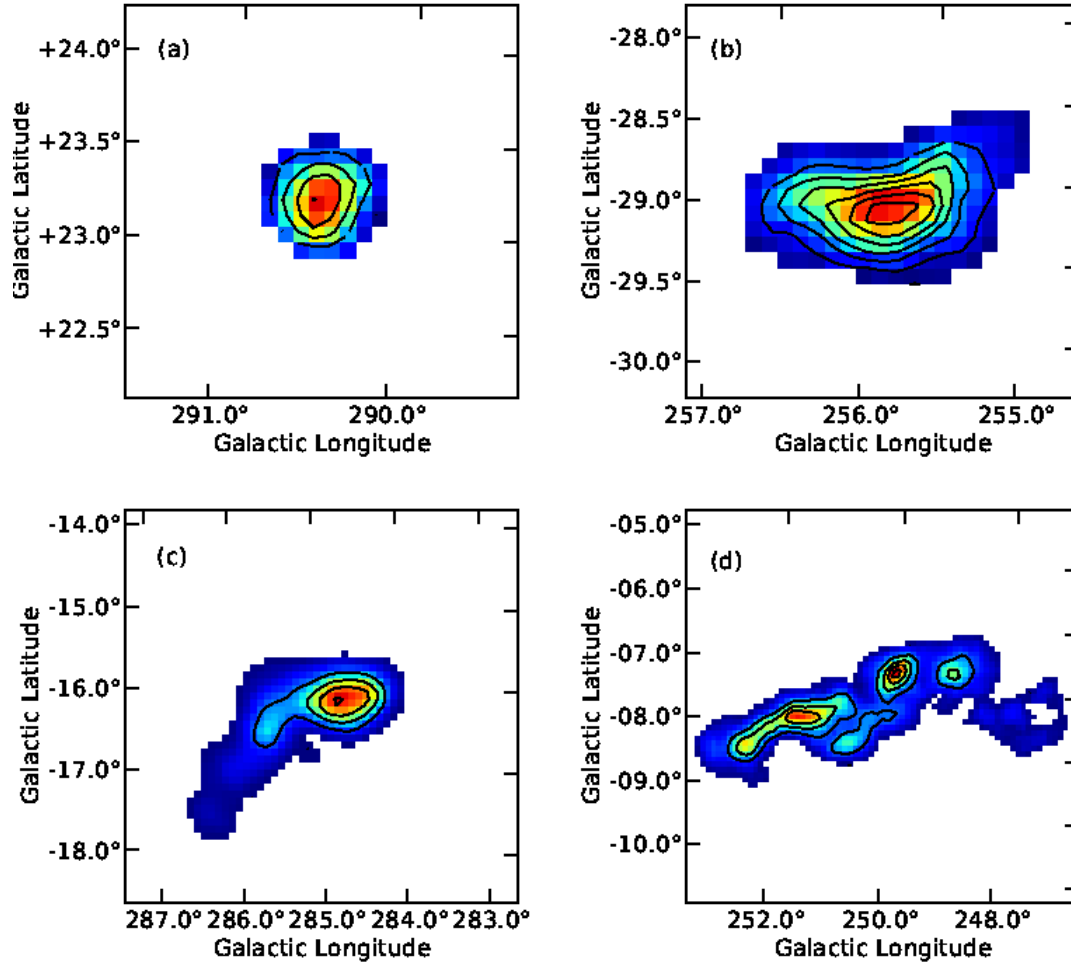


Fig. 13.— Examples of cloud morphological types: (a) symmetric cloud; (b) bow-shock shaped cloud; (c) head-tail cloud; (d) complex and irregular cloud.

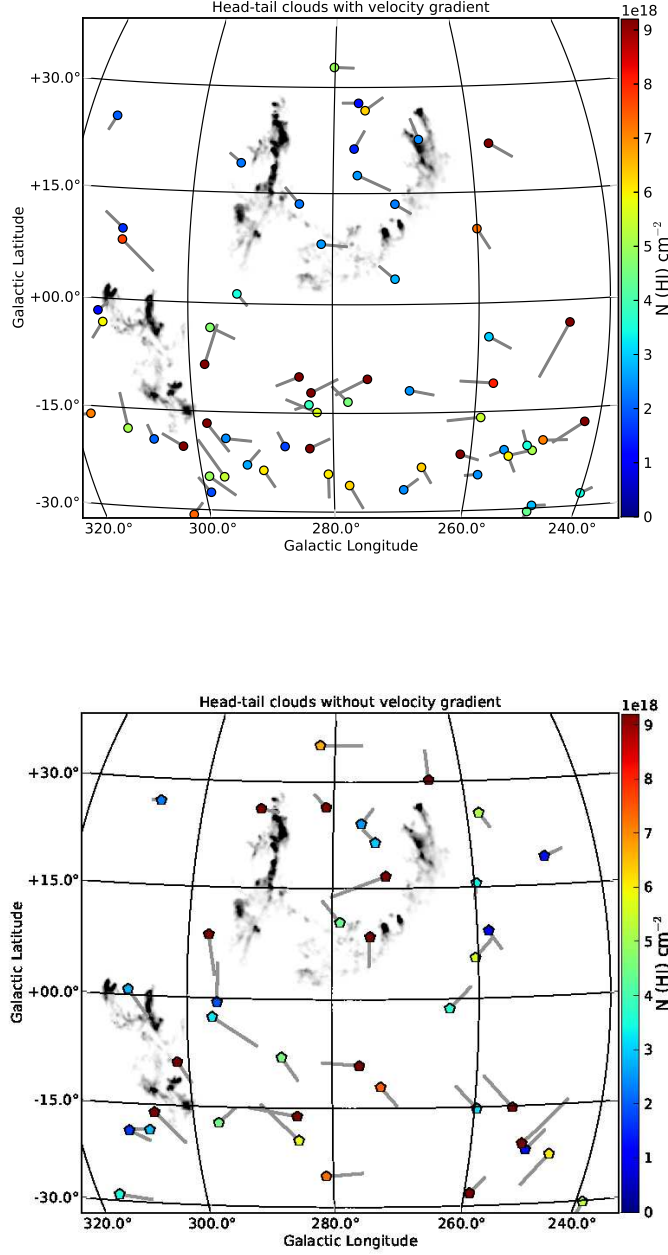


Fig. 14.— Sky distribution of identified head-tail clouds with velocity gradient (top panel) and without velocity gradient (bottom panel) in the region of the Leading Arm. The colors indicate the peak HI column density of each head-tail cloud according to the color bar scale on the right side. The head and tail have been enlarged from its original size in these plots. The derived position angle of head-tail clouds has been adjusted manually to represent the actual pointing direction whenever necessary (see §5.1).

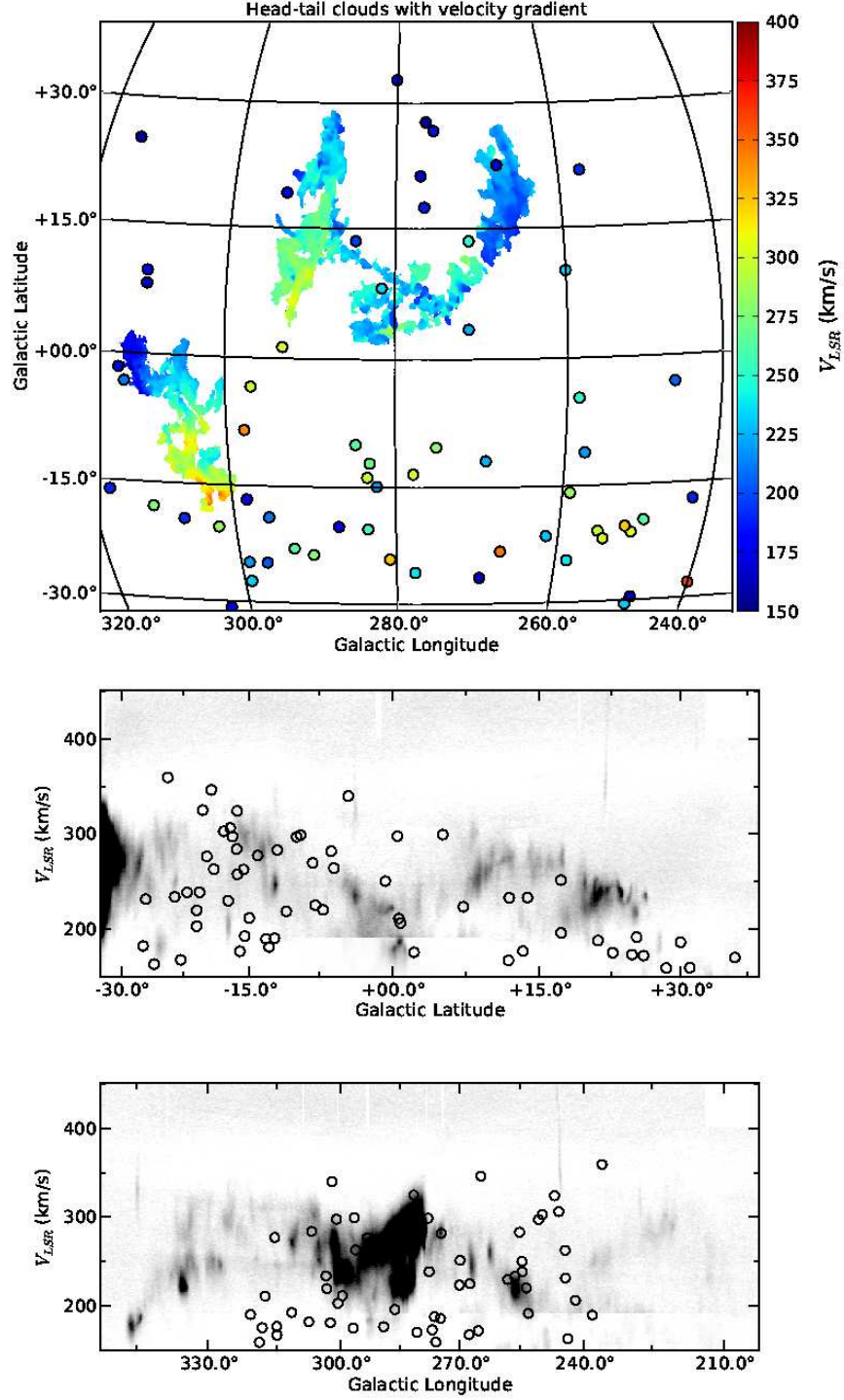


Fig. 15.— The top panel shows the sky distribution of identified head-tail clouds with velocity gradient (HT) in the region of the Leading Arm. The colors represent the V_{LSR} of each head-tail cloud according to the color bar scale on the right side. The bottom two panels show the HT clouds superimposed on position-velocity maps.

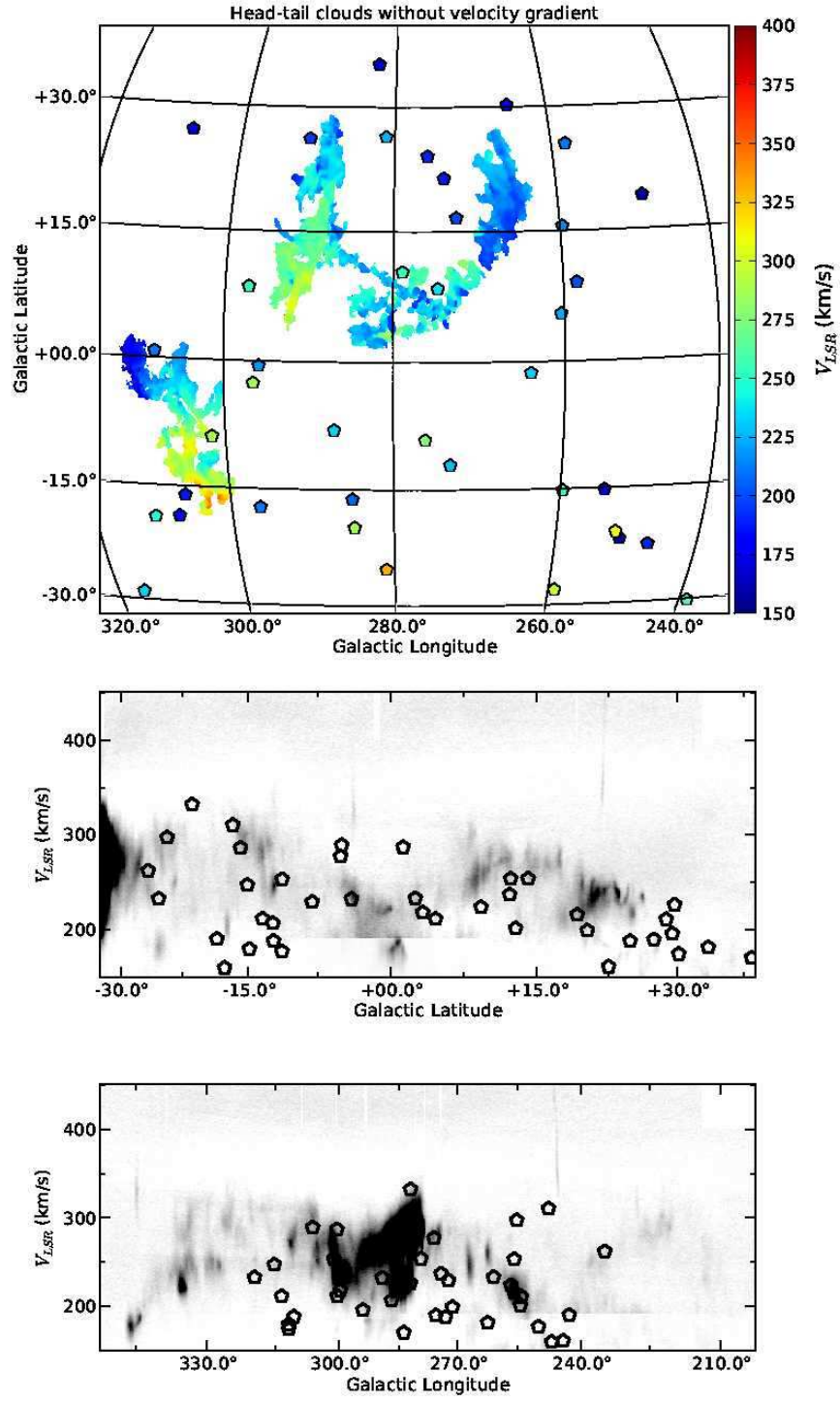


Fig. 16.— Same as Figure 15, except showing head-tail clouds without velocity gradients.

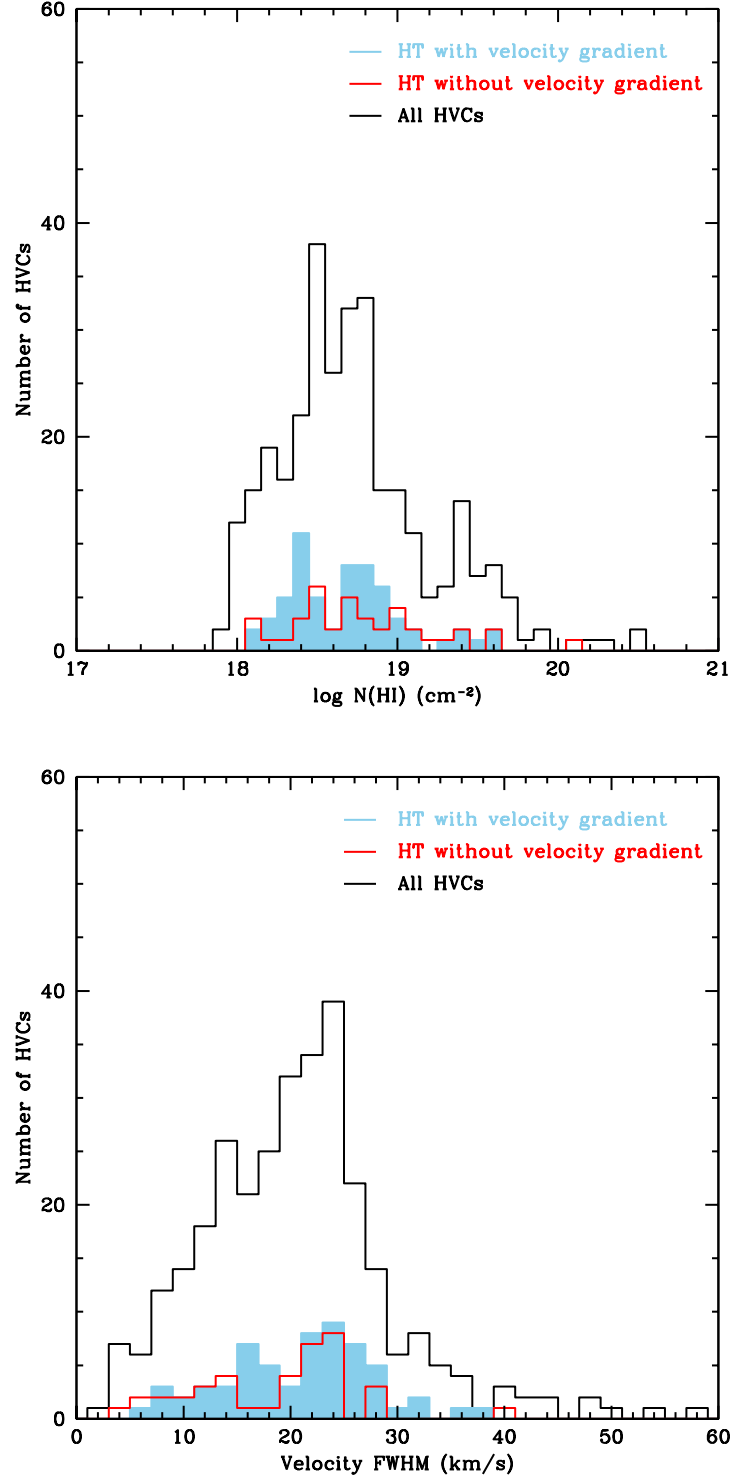


Fig. 17.— Histograms of peak HI column density (top panel) and FWHM velocity (bottom panel) of HVCs in this catalog. The black, blue and red represent all HVCs, head-tail clouds with velocity gradient and head-tail clouds without velocity gradient identified in GASS data, respectively. Only clouds with velocity FWHM less than 60 km s^{-1} are being plotted in the histogram.

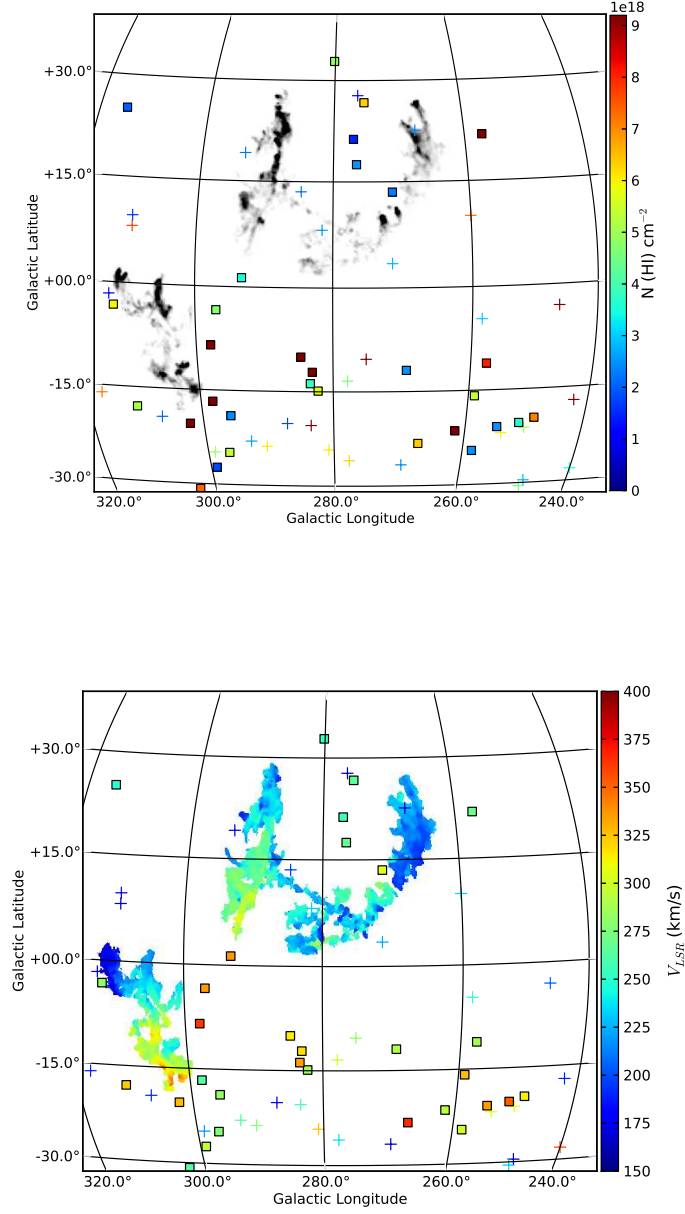


Fig. 18.— Sky distribution of head-tail clouds with positive velocity gradient (pHT; pluses) and with negative velocity gradient (nHT; squares). See definition in §5.1. The top and bottom panels show the distributions in peak HI column density and V_{LSR} , respectively. The colors indicate the values according to the color bar scale on the right side.

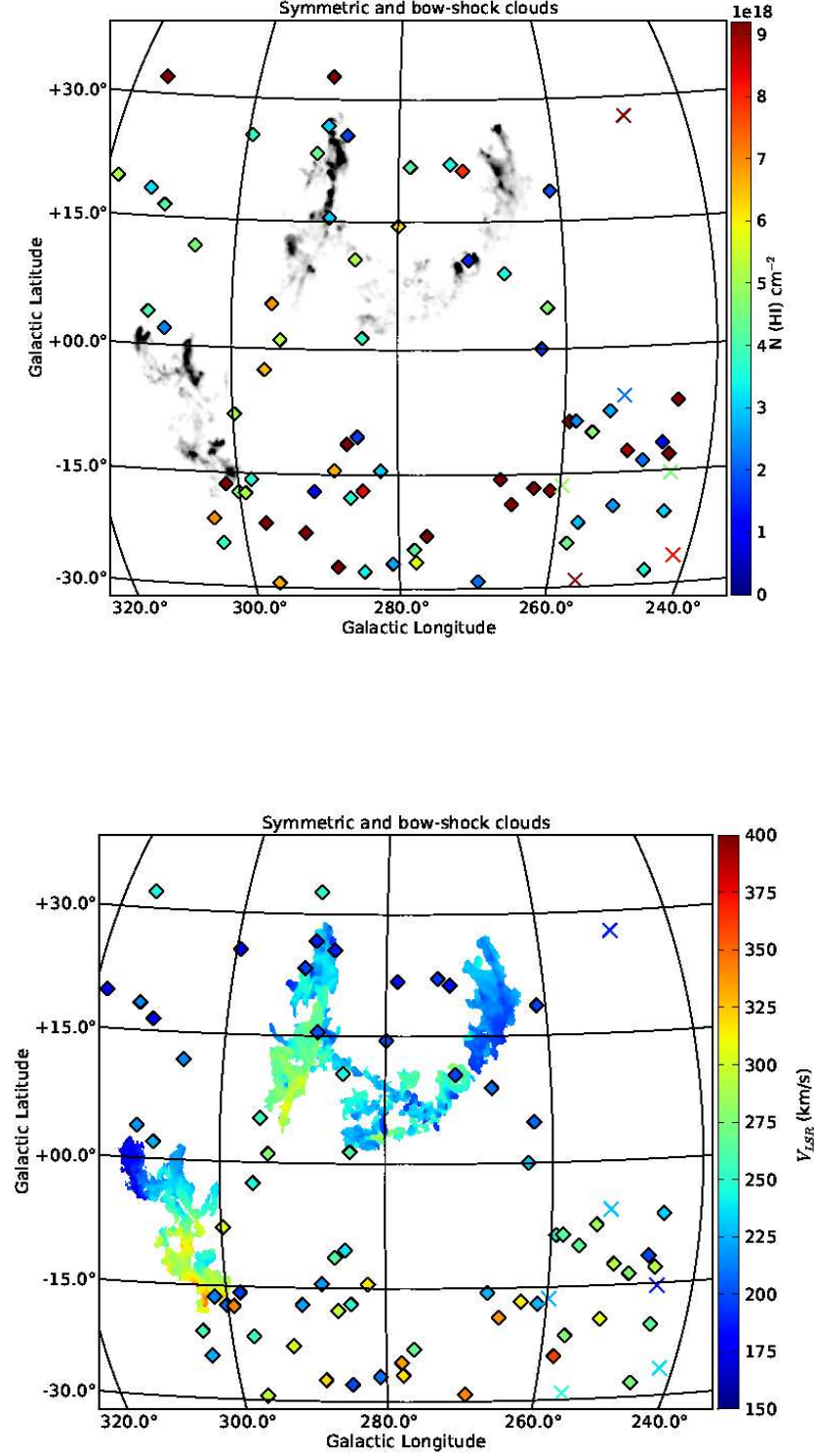


Fig. 19.— Same as Figure 18, except showing the sky distributions of symmetric (diamond) and bow-shock shaped clouds (crosses).

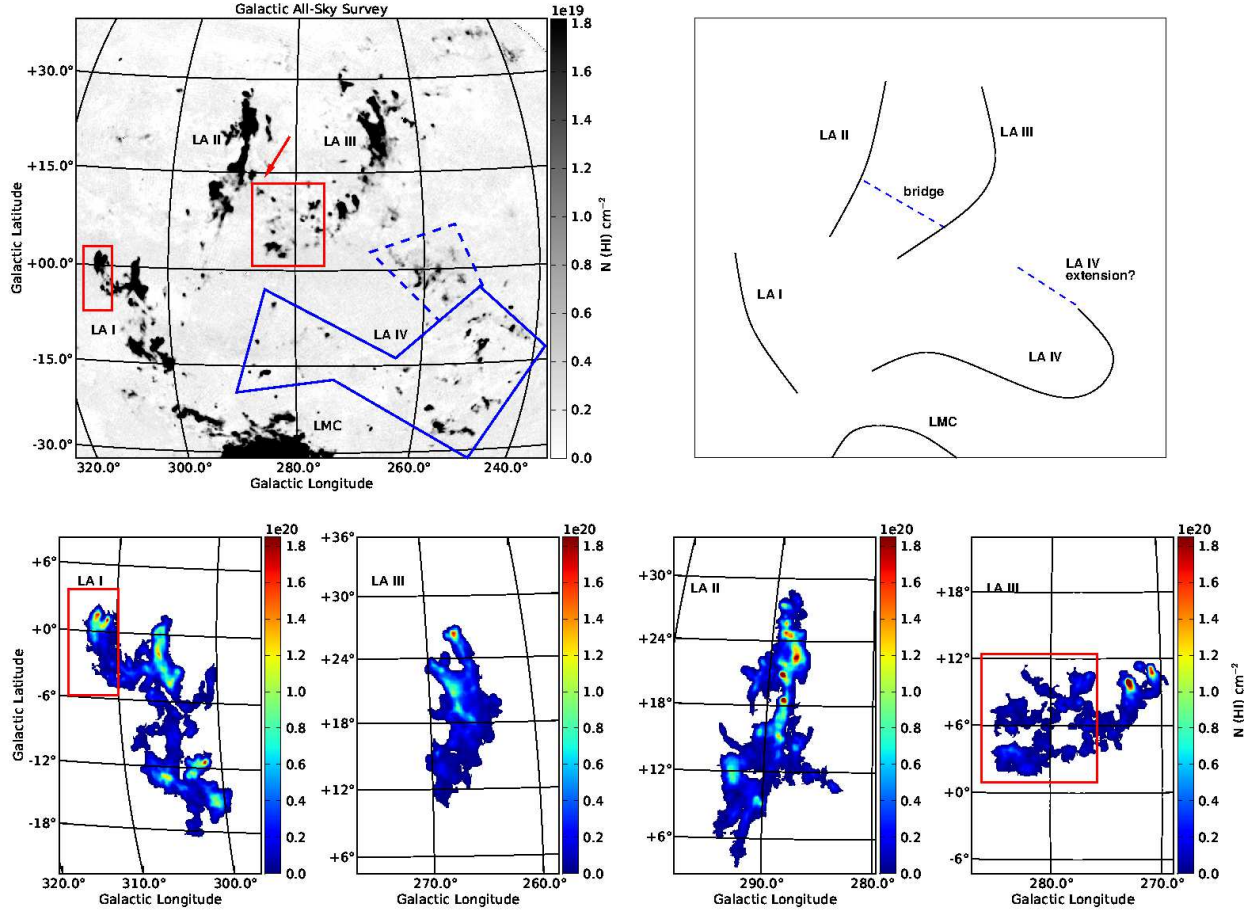


Fig. 20.— The top left figure shows the integrated HI column density map in the region of the Leading Arm. The red boxes highlight the extended features of LA complexes as seen in GASS. The arrow indicates the “bridge” structure connecting LA II and second cloud complex of LA III. The blue box shows the location of the new cloud population, namely LA IV. The blue dashed box marks the boundary of possible extended feature of the LA IV. The top right figure is a schematic diagram of the LA features and the LMC. The bottom subfigures show individual integrated HI column density maps of LA complexes as identified by *Duchamp*. The red boxes match the position as shown in the top figure.

Table 1. GASS catalog of detected sources in the region of the Magellanic Leading Arm.

ID	Designation	V_{LSR}	V_{GSR}	V_{LGSR}	FWHM	$F_{\text{int}}^{\text{a}}$	T_{B}	N_{HI}	Semi-major	Semi-minor	PA	Flag ^b	Classification ^c
(1)	($gl \pm gb + V_{LSR}$) (2)	km s ⁻¹ (3)	km s ⁻¹ (4)	km s ⁻¹ (5)	km s ⁻¹ (6)	Jy km s ⁻¹ (7)	K (8)	10 ¹⁹ cm ⁻² (9)	° (10)	° (11)	° (12)	(13)	(14)
63	HVC+236.9−19.1+174	...	...	...	...	...	...	...	...	...	...	M	IC
64	HVC+307.2+26.8+174	174.0	17.5	−60.2	12.4	2.1	0.20	0.23	0.2	0.2	−54	...	:HT
65	HVC+273.5+24.5+174	174.2	−25.6	−79.9	4.3	1.3	0.17	0.09	0.3	0.2	54	...	IC
66	HVC+251.3+36.6+175	174.5	7.3	−28.0	48.0	174.8	0.62	2.63	...	...	...	...	IC
67	HVC+293.3+19.1+175	174.8	−16.2	−85.5	11.5	3.1	0.20	0.22	0.3	0.2	35	...	HT
68	HVC+313.9−01.7+175	175.2	16.8	−54.0	8.7	1.5	0.21	0.12	0.3	0.2	−37	...	HT

Note. — Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

^aCorrected F_{int} .

^bSR: the detection lies at the edge of the spectral region; M: the detection extends over to the masked Milky Way emission region; E: the detection is next to the spatial edge of the image.

^cHT: head-tail cloud with velocity gradient; :HT: head-tail cloud without velocity gradient; S: symmetric cloud; B: bow-shock cloud; IC: irregular/complex cloud.